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Electric and Plug-In Hybrid Vehicles

Advanced Simulation Methodologies

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Foreword

When Bogdan Varga asked me to write the Foreword to his book on "Electric and Plug-In Hybrid Vehicles Advanced Simulation Methodologies" I was indeed honored: Generally, people who are asked to write Forewords are those who matter to the author.

I met Bogdan Varga in 2007 at a conference for automotive engineers organized by the Technical University of Cluj. I had just taken over the job of Sales Manager for Central and Eastern Europe for Instrumentation and Test Systems. I was impressed by the determination and ardor Bogdan showed in his scientific work as well as his professionalism and effectiveness in preparing big research projects.

In 2010, AVL together with Technical University of Cluj built a Laboratory for Testing, Research, and Certification of Internal Combustion Engines, AVL delivering not only testing equipment but also research tools as well as software for data processing and simulation.

Since then the Technical University of Cluj and AVL have been in close contact, exchanging knowledge and experience in research, focusing mainly on methods to deal with the increasing complexity of powertrains.

The complexity and diversity of future powertrain systems elevates dramatically. One driving factor is given by enhanced legislative requirements, such as reduction in CO_2 fleet emissions and pollutant emissions under real-world driving conditions (RDE).

Another factor is increased customer demands as positive driving experience, safety, agility, comfort, and confidence in driver assistance systems. On top of this, shorter model cycles and moderate cost of ownership are demanded.

One key to managing this complexity is to use and integrate virtual development environments into the development process of powertrain systems.

In the past, for example, the functional integration of subsystems into a complete vehicle system was done within a system integration using only real hardware. Today this is combined with virtual environments, too. In future this integration will be done in purely virtual environments in early stages of development.

With the book's approach Bogdan provides an excellent tool for researchers working on these challenges: he not only describes the simulation method of complex powertrains, but also explains how to build a working virtual development environment for classical, hybrid, and electrical powertrains.

I am convinced that Bogdan's book will be a big help for any researcher to better understand the process of modeling and simulation of complex powertrains and to start out in creating a virtual laboratory.

Graz
April 2015

DI Stefan Kanya
Sales Manager Central and Eastern Europe
AVL List GmbH

Acknowledgments

The writing process of this book consumed a huge amount of work, research, and documentation, but in the end, the effort is dedicated to those who are interested in applicative use of advanced modeling and simulation technologies for the optimization of energy efficiency in automotive electric and hybrid powertrains.

First of all, we are deeply grateful to AVL LIST GmbH, A-8020 Graz, Hans-List-Platz 1 (www.avl.com) for their essential logistic support, availability, and also for provision of their high-level professional expertise and technical support in the writing process of the book. Their advice definitely increased the scientific and applicative quality of book.

Still, all of this would not have been possible if we did not have a strong and permanent support of leadership (Prof. Nicolae Burnete, Ph.D.) and our colleagues from Automotive Engineering and Transport Department of Technical University of Cluj-Napoca, Romania. Therefore, we would like to extend our sincere thanks to all of them.

Nevertheless, we express our gratitude toward our families for their support, understanding, and encouragement, which helped us permanently throughout the preparation of the book.

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Dan Moldovanu
Calin Iclodean

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Abbreviations

4WD	Four Wheel Drive
ABS	Anti-lock Braking System
ACC	Autonomous Cruise Control
ARB	Anti-Roll Bar
ASC	Anti-Slip Control
AST	Advanced Simulation Technologies
BMEP	Brake Mean Effective Pressure
CIT	CarMaker Interface Toolbox
CTF	Concerto Transport File
CVT	Continuously Variable Transmission
DLL	Dynamic Link Library
DoE	Design of Experiments
DVA	Direct Variable Access
EFG	Energy Flow Graphics
EMS	Engineering Measurement System
EPS	Electric Power Steering
ESP	Electronic Stability Program
EV	Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FWD	Front Wheel Drive
GHG	GreenHouse Gas emissions
GIS	Geographic Information System
GPS	Global Positioning System
GUI	Graphic User Interface
GXF	GPS eXchange Format
HEV	Hybrid Electric Vehicle
HPS	Hydraulic Pneumatic Supplies
HTML	HyperText Markup Language
ICE	Internal Combustion Engine
iFD	Ratio of Final Drive
IFF	Input From File

ISG	Integrated Starter Generator
iTR	Ratio of Final Transmission
KML	Keyhole Markup Language
NEDC	New European Driving Cycle
PHEB	Plug-in Hybrid Electric Bus
PID	Proportional Integral Derivative
PNG	Portable Network Graphics
RE	Range Extender
RPN	Reverse Polish Notation
SAM	System Analysis Mode
SOC	State Of Charge
SRT	Single Ratio Transmission
VVE	Virtual Vehicle Environment
XML	eXtensible Markup Language

Chapter 1
Principles of Modeling and Simulation Processes

The development of humanity, along historical evolution, was based on continued and specific activities of environmental knowledge. The knowledge accumulated over time was used to achieve the necessary leaps of progress in civilization (in each historical stage of development of human society).

The knowledge process of the environment was achieved through specific operations approach, nearby and reconstruction of reality. Instruments relied on knowledge can be classified into two main classes:

- Tools (instruments) that provided data collection, data objects, and phenomena that reflect the properties of the surrounding environment. Data collection was made possible by direct observation, description, and measurement of natural phenomena.
- Tools (instruments) for data interpretation, reflected by human thinking. The thinking process used specific analysis, synthesis, and deductive methods. These methods have led to the development of further assumptions, judgments, valid laws, and/or general theorems for the process and/or studied phenomenon.

Until modern times, activities were predominantly based on observation and measurement of a particular aspect of nature and/or the environment, with immediate finality to ease human existence. With the historical evolution of human civilization and philosophical approaches of human existence, observation and measurement provided (made available) a huge number of data.

This process allowed studying them and also observation of well-established particularities (their repeatability), depending on the studied phenomenon. Logically, the next step was to lay patterns that can be allocated to other phenomena and/or subjects, with predictable results.

Thus emerged the first attempts to modeling the environment, with the primary definition of the concept of system. Realizing this approach was in replacing the natural source (physical) system with an equivalent abstract one (using observation and measurement tools) that can be analyzed further using specific tools.

The system was an entity composed from sharp features and high generality of the studied problem, but which also provides the link between the input parameters (observable and measurable) and the output parameters (of predictability).

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With the definition of system notion and the development of a mathematical device to realize the connection between input parameters, output parameters, and operating parameters of the system modeling process began to be increasingly used in all areas related to human activities.

At present, generally system theory defines the concept of "system" as being a well-ordered and structured multitude of interlinked elements well determined within the system (but unrelated to the external environment of the system).

Connection between the external environment and the system is achieved through use of system parameters that characterize the input/output relationship of the entities presented (environment/system).

Expression of relations between input and output values of the systems is achieved by using sets of values associated to input/output values or by using mathematical functions.

The system is characterized by allocated sets of sizes that are assigned certain attributes. Static attributes are characterized by fixed values (constants) called "system parameters." Dynamic attributes receive different values (for different times) and are called "descriptive variables of the system."

Further, the association between constant and variable sizes (considered to be inner entities of the system) is reached to a combination of a physical system with an abstract mathematical model.

Depending on the possibility of initiating a modeling process (the award of a model to real phenomena), systems can generally be classified according to the sets of variable values and depending on the structure.

Classification of the systems based on the set of values of variables is done considering the variable types (analog or digital) and after the variation in time of variables (continuous, discontinuous, and discrete).

Further, the concept of "model" is a representation of the essential characteristics of a system, in order to determine its behavior and also of variation of output parameters to the input parameters.

Modeling, as activity and as processes of developing an accurate model related to a source system, follow the following steps (Fig. 1.1):

- Building of basic (initial) model;
- Model analysis;
- Comparing results;
- Correction of model.

The immediate and major advantages of using models to study the behavior of a system are:

- Availability for study and analysis are larger than of systems source;
- Lower cost and time of implementation, testing, and experimentation;
- Ease of changing the structure of the model (depending on the intended purpose);
- Provides clues about the behavior change of source system, based on the variation in the variables considered in the study.

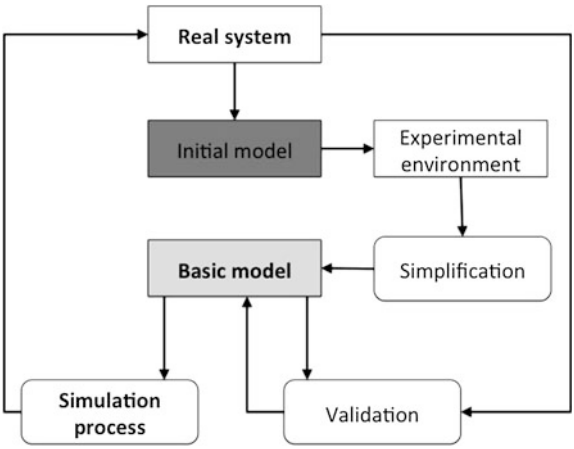


Fig. 1.1 Basic structure of modeling theory

Once the observations based on the source system can provide a model to characterize its evolution, according to the variation of the variables considered, it can proceed to the next phase, namely the simulation process.

The simulation process can be defined, in general terms, as all functional and/or operational activities on a model that representing the image of a source system necessary to be analyzed.

Because the model attached to a source system consists of one or more mathematical expressions (in the form of equations that describe the relationships between model components), simulation processes are performed using computer simulation.

There are a total of three main activities in the realization of a simulation process: development, testing, and operation (Fig. 1.2).

The development work refers to the integration of mathematical models that define the system state and variables into informatics codes (lines of code, programs) that can be processed further using computers.

In the testing phase of the model is required a check of its behavior at specified conditions (if implementation of the model takes into account the initial assumptions).

The results should be analyzed carefully to achieve assessing the fairness of the model, by analogy with the data obtained direct from source system (under certain known conditions).

If the model is valid and the simulation process is functional then the third phase is run, the operating activities of the model.

The operation of model may possibly impose some conditions on the source system studied, conditions that would not have been possible through direct experiments on the physical source system.

The results should be analyzed and used both to improve the model and to optimize source system behavior depending on the initial objectives of the research.

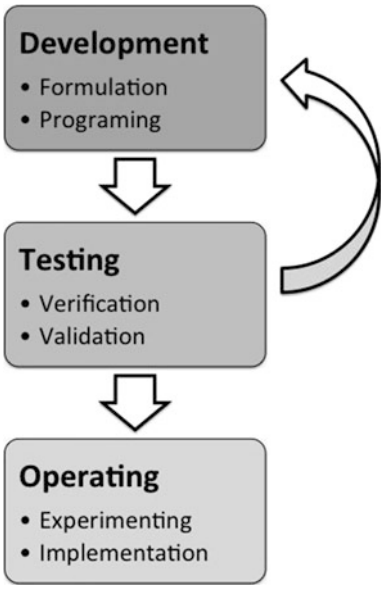


Fig. 1.2 General structure of a simulation process

Nowadays, the concept of 'mobility' best characterizes human society. The mobility of goods, people, and ideas actively participate directly in the technological, economic, social, and cultural progress of humanity (as a whole).

In the transport domain there are specific requirements relating to environmental protection, which require vehicle manufacturers to make necessary arrangements to find technological solutions to integrate the transport domain in a general and necessary structure of human society development on a sustainable basis [1].

The transportation sector is currently responsible for over 20 % of emission of greenhouse pollutants, emissions that directly affect the climatic conditions of the planet. Increased emissions in conjunction with achieving the maximum degree of natural regeneration of the environment, lead to serious problems related to pollution [2–4]. Naturally, the European Union (mainly) formulated policies and actions to reduce emissions from activities associated with human society.

The major challenge in this regard, for the transport domain, is to reduce immediately greenhouse gas emissions (GHG) discharged into the atmosphere.

Because pollutant emissions from vehicles are caused by combustion of a fuel (generally fossil fuels), increasing the efficiency and effectiveness of vehicle's powertrain is constantly the focus of attention of researchers from the automotive industry.

Competitiveness and competition in this field compel the use of means and methods of research and development that is economically viable (reduced costs and time to market deployment of new and improved technological solutions).

Modeling various natural or artificial processes and phenomena in engineering is achieved by applying and performance of complex mathematical models (that take

into account multiple hypotheses and wide range of determinants factors) using ultrafast informatics programs on electronic processing in computerized environments.

For this, numerical methods are applied to discretize equations that define the condition and/or evolution of the considered technical system. Using high potential and processing speed of information available from today's computers (for analysis of complex data sets), equations that offer multiple connects between different factors of different sizes can be determined in real time.

Using this method, the solving procedures of complex problems in processing are substantially reduced, to temporal sequences of discretized sizes, with immediate benefit to achieve economies of time and labor. Mathematical developed code is implemented further as one of the appropriate programming languages.

Some of these programming languages have the advantage of object-oriented programming capacity and accessible syntax for user. Applications developed using programming codes allow simulation of functional systems and sub-systems that compose the functional structure of a vehicle.

Using software tools existing in this area, simulations can be developed, controlled, and coordinated (at the same time) to achieve results and solutions to optimize and improve the performance of vehicle's technical systems and are analyzed in terms of performance and operating efficiency.

These applications allow or build linear or nonlinear models (depending on the complexity and processing potential of software program), computer processing lines and matrix, characterized by the boundary conditions at various points (areas), and by the conditions of the initial state of the considered technical system.

Modeling and detailed analysis of the powertrain system has been, is, and will be considered permanently in research worldwide. Due to complexity of the technical structure of a powertrain, research focus is on the study of a single component, or of the entire powertrain system, or by studying the interactions of this with the general constructive-functional system of a vehicle [5, 6].

Walker and Zhang [7] studied the influence of engine torque harmonics, model degrees of freedom, and dual mass flywheels on the transient response of a vehicle powertrain equipped with a dual clutch transmission for two powertrain models. Their results by modeling and simulation process indicate that degrees of freedom, engine model, and flywheel model all contribute significantly to variance in powertrain response under each configuration.

Kouroussis et al. [8] present an effective formulation to model an automatic transmission (based on Del's method), to evaluate the vehicle performance in the early development stage of a powertrain design. The efficiency and accuracy of modeling process was validated taking into consideration the application of simulation results on two realistic cases (Chrysler 45RFE and Aisin Warner 55–50 SN powertrains).

To analyze the advantages of the hybrid powertrain based on the component characteristics and to define an optimum powertrain configuration with respect to the applied drive cycle, a combined simulation and analytical analysis of the

energy conversion efficiency in parallel hybrid powertrains were performed by Katrasnik [9].

Damiani et al. [10] show that a vehicular powertrain can be thought as an energy conversion chain, each component being characterized by its self-efficiency. Through a validated MATLAB®/Simulink™ model (designed to indicate the powertrain energy breakdown), simulations were carried out to evaluate the fuel saving associated to a series of powertrain management logics to minimize engine losses, to recover the reverse power in deceleration and braking, and to eliminate the uselessness of engine cycles.

Klein et al. [11] performed an original approach on powertrain modeling and simulation. Their research validates an artificial wavelet neural network (or wavenet model) combined with artificial bee colony optimization (as a swarm intelligence paradigm), to model powertrain components of a truck engine. Simulation results show that the artificial wavelet neural network approach can be a promising technique in powertrain components modeling; the proposed artificial bee colony approach allows modeling the dynamical behavior of powertrain components of a truck engine.

From the point of view of emerging technologies for transports, a novel hybrid genetic algorithm for modeling and simulation of the powertrain and control parameters in plug-in hybrid electric bus (PHEB), for simultaneous optimization with trade-off between economy and dynamic performance was proposed by Li et al. [12].

Moreover, the study by Wang et al. [13] shows the effects of different EV powertrain topologies on the energy efficiency, vehicle ownership cost, and life-cycle greenhouse gas (GHG) emissions of EVs. Energy-based vehicle simulation model proposed include the regenerative braking function and battery degradation prediction method to be established first. An optimization scheme was used to combine the energy-based vehicle simulation model in order to minimize the electric energy consumption under various scenarios and driving conditions.

Ryu et al. [14] focused on possibilities to use a novel fuzzy controller based on an adaptive membership function for optimum power management of a fuel cell hybrid electric vehicle (FCHEV). The fuzzy controller is optimized using a genetic algorithm, and the optimization process is accomplished through simulation (for a given driving cycle) in order to achieve the best performance in terms of minimum fuel consumption and State of Charge (SOC) maintenance.

Xie et al. [15] studied the effects a novel fuel cell Li-ion battery hybrid powertrain using a direct parallel structure with an ultracapacitor bank on vehicle's efficiency. ADVISOR simulation tool based on the vehicle model parameters was used to simulate the powertrain's energy flow for a specific driving cycle (UDDS cycle).

The random examples presented above are just a few examples of the many research studies that use specific tools for modeling and simulation processes of a vehicle's component (s) and/or technical systems.

It can be noted that the modeling and simulation processes of any technical system are important tools in research work, offering a large number of data that can

be investigated and then used further to optimize the functional and technical parameters of the studied system.

Modeling and simulation approach of technical and functional characteristics that influence the powertrain is widely presented in the subsequent chapters of this book. For modeling and simulation processes the software packages CRUISE (AVL List GmbH) and CarMaker (IPG GmbH) were used. These software packages were developed for precision applications in analysis and dynamic performance of a vehicle's technical systems.

Detailed methods, methodologies, and approaches to the immediate application of modeling and simulation processes are presented, to analyze the vehicle's technical systems and/or sub-systems of which it is composed, in order to provide a powerful tool to any researcher that wants to use immediately and apply these modeling and simulation software packages in research activities.

The structure of each chapter allows any researcher to make easy the process of modeling and simulation of a vehicle's technical system, according to its specific needs and requirements. This is possible due to detailed presentation of the algorithms for construction, operation, and running of the presented models.

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Chapter 2
Mathematics Behind the Models

The theory that is presented in this chapter represents the mathematical models developed by AVL CRUISE team and points out the characteristic of each vehicle component used in the models created in the following chapters.

2.1 Vehicle (V)

The Vehicle is one of the main objects in a model. This component contains general data of the vehicle, such as nominal dimensions and weights. One and only one vehicle component is needed in the model. Road resistances and dynamic wheel loads are calculated for road and dynamometer runs based on the dimensions and the load state. The wheel loads are calculated, taking motion into account (e.g., from acceleration, aerodynamic drag, rolling resistance). The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated [1].

2.1.1 Properties

Switch Variation
With this switch the vehicle can be given free for variation. For the vehicle the drag coefficient and the vehicle mass can be varied. The setup of the variation parameters is done in the folder.

Switch Output
If this switch is activated a result output for this component is made.

Driving Resistance Switches
Activation of one or more of the following five driving resistance models. The associated resistance model can be calculated in one or more AVL CRUISE

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Calculation Task when selected. Also the required data input for the activated resistance models has to be done. In every task the selection button 'Driving Resistance' determines which of the activated models will be really used in the task calculation. Every model which is chosen in a task, has also to be activated in the vehicle properties window, otherwise the calculation stops with an error message.

Switch Driving Resistance: Physical
The driving resistance is defined by the physical values (drag coefficient, rolling resistance).

Switch Driving Resistance: Function with Reference Vehicle
The driving resistance is defined by three parameters. The defined values are converted from the reference vehicle to the actual one.

Switch Driving Resistance: Characteristic with Reference Vehicle
The driving resistance is defined in a characteristic as function of the vehicle velocity. The defined values are converted from the reference vehicle to the actual one.

Switch Driving Resistance: Function without Reference Vehicle
The driving resistance is defined by three parameters. The defined values are used without a reference vehicle.

Switch Driving Resistance: Characteristic without Reference Vehicle
The driving resistance is defined in a characteristic as function of the vehicle velocity. The defined values are used without a reference vehicle.

Selection Button Driving Resistance Input Options
Standard
From Coasting Characteristic
From Deceleration Interval Characteristic
'Normal' input of the required values for Resistance Function or Resistance Table.

Selection Button Driving Resistance Input Options

Standard
From Coasting Characteristic
From Deceleration Interval Characteristic

When the switches 'Driving Resistance: Function with Reference Vehicle' or 'Driving Resistance: Characteristic with Reference Vehicle' are activated, the option 'Driving Resistance from Coasting Characteristic' can be chosen. By selecting a conversion button (located at the Coasting Characteristic), the Resistance Function/Resistance Table is calculated using the values of the Coasting Characteristic. The Coasting Characteristic is defined by vehicle velocity, depending on the time since the coasting measurement started.

Selection Button Driving Resistance Input Options

Standard
From Coasting Characteristic

From Deceleration Interval Characteristic
This option is available when the switches 'Driving Resistance: Function with Reference Vehicle' or 'Driving Resistance: Characteristic with Reference Vehicle' are activated.

The required values are converted from the so-called 'Deceleration Interval Characteristic'; every input row of this characteristic defines the time for a deceleration (e.g., velocity interval = 10 km/h) around a specified vehicle velocity. For example, the defined time at 120 km/h corresponds to the time needed for the vehicle to decelerate from 125 to 115 km/h. Similar to the conversion from coasting characteristic, there are options for 'Truncate left' and 'Truncate right' to cut off data which might have a bad influence on the conversion results. Additionally, there is an input field for the definition of the velocity interval.

Selection Button Aerodynamic Coefficients

Drag Coefficient Constant
Additional Aerodynamic Coefficients—Data Bus Dependent
Drag Characteristic
The constantly defined drag coefficient is used for calculation.

Selection Button Aerodynamic Coefficients

Drag Coefficient Constant
Additional Aerodynamic Coefficients—Data Bus Dependent
Drag Characteristic
Further option for modification of aerodynamic parameters (drag coefficient, lift coefficient front axle and lift coefficient rear axle) which can be modified according to any Data Bus set value:

that means opening and closing of aerodynamic spoiler as function of any Data Bus set value (with hysteresis).

Remark: for stationary iterations the upper hysteresis values are used.

Selection Button Aerodynamic Coefficients
Drag Coefficient Constant
Additional Aerodynamic Coefficients—Data Bus Dependent
Drag Characteristic
In this case the drag coefficient is interpolated from the drag characteristic, depending on the value of the Data Bus input x-axis for drag modification.

Switch Lift Effect Consideration
If this switch is activated, the wheel lift forces are considered in the calculation. Otherwise there are no lift coefficients required (lift coefficient front axle/lift coefficient rear axle) and the lift forces are internally set to zero. This switch can only be activated if the Selection Button **Driving Resistance** is set to *physical* or to *Function with reference vehicle* or to *Function without reference vehicle.*

Switch Cornering
With this switch the cornering functionality is activated. In the tasks Cycle Run, Full Load Acceleration, Cruising and Braking this function can also be activated and then the Characteristic Values under the influence of the curvature radius for cornering are computed.

Cornering can only be calculated for the vehicle. If there is a trailer or multi-axle trailer in the model, this part of the calculation will not be started.

Switch Crosswind Influence
Depending on cornering it is possible to consider the influence of crosswind.

Switch Cold Start Correction 1–5
If one or more of these switches are activated, the cold start factor is multiplied with the actual fuel consumption if all other selections are done in the right way.

Switch Cycle 1–5
With these switches, up to 5 cycles can be activated for definitions of temperature characteristics.

Switch Temperature Curve 1–5
With these switches, up to 5 temperature characteristics can be activated for every activated cycle.

For the tasks 'Cycle Run' and 'Cruising,' these temperatures can be connected via Data Bus to different components like the engine. In all these components, the selections have to be set properly so that the temperature from the Data Bus is used, e.g., in the engine, **Temperature** has to be set to **from Data Bus**.

2.1.2 User-Defined Variables

V_N	Gas Tank Volume	m^3

The Tank Volume is the gas (fuel) tank volume of the vehicle. It is used to calculate the distance range the vehicle can reach with the actual fuel consumption.

$\Delta T_{\text{under-bonnet}}$	Temperature Difference Engine/Environment	K
$\Delta p_{\text{under-bonnet}}$	Pressure Difference Engine/Environment	mbar

The temperature and the pressure difference serve for the correction of the intake conditions. The differences in the conditions of the environment and the engine compartment have to be defined. These values are used in the power correction on environment conditions (see *Chapter* '*Power Correction on Environment Conditions*' in engine component).

Nominal Dimensions

$l_{V,vcp}$	Distance between Hitch and Front Axle	mm

The distance between hitch and front axle is the horizontal distance between the coupling point for the trailer and the front axle. In the case of a **Semi-trailer Truck**, this value can be smaller than the wheel base.

$l_{V,fr}$	Wheel Base	mm

Wheel Base is the horizontal distance between the front and the rear axle (Fig. 2.1).

$h_{V,cd}$	Height of Support Point at Bench Test	mm

If the car is driven on a chassis dynamometer the vehicle is fixed somewhere to the wall. The height of this support point on the vehicle (vertical distance between the ground and the support point) has to be given here. This is used for the calculation of the wheel loads because due to this height there is a moment that affects the wheel loads (Fig. 2.2).

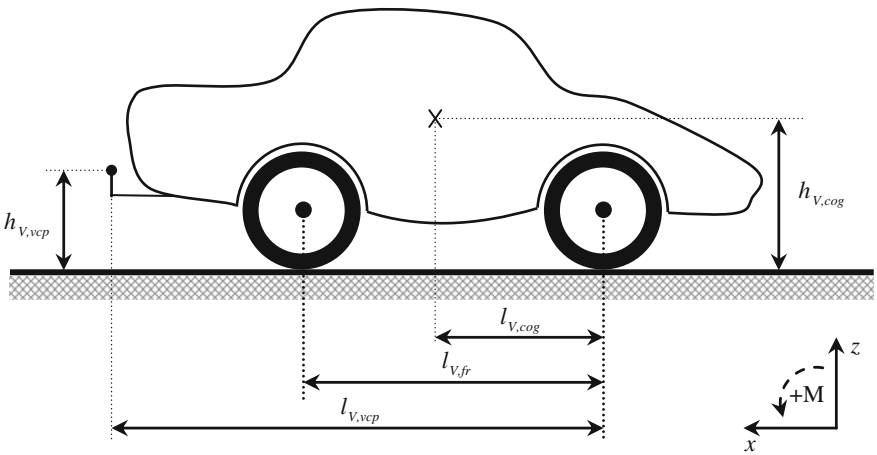


Fig. 2.1 Vehicle nominal dimensions [2]

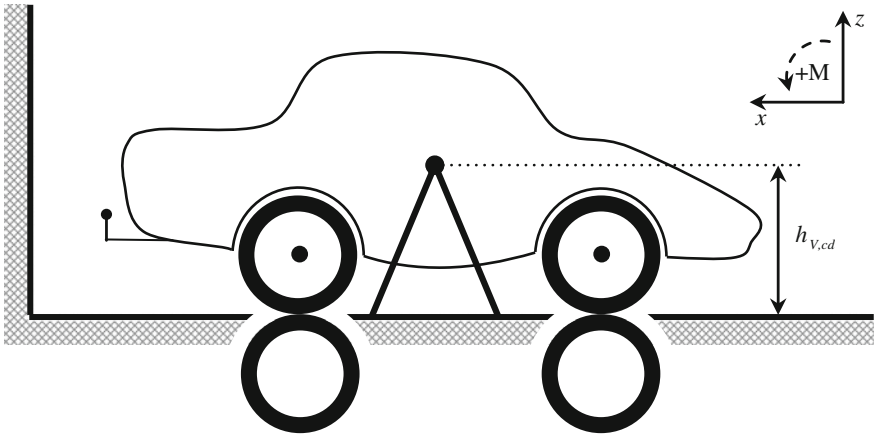


Fig. 2.2 Support point at bench test [4]

Every calculation can be run with three different load states ($z_{V,load}$): empty, half, and full

- Empty: means that the weight of the vehicle equals the Curb weight
- Full: means that the weight of the vehicle equals the Gross weight
- Half: means that the weight of the vehicle equals the middle of the Curb and the Gross weight

Load-Dependent Characteristics

$l_{V,cog}$ ($z_{V,load}$)	Distance of Gravity Center of the Vehicle Dependent on the Load State	mm
$h_{V,cog}$ ($z_{V,load}$)	Height of Gravity Center of the vehicle dependent on the Load State	mm
$h_{V,vcp}$ ($z_{V,load}$)	Height of Hitch dependent on the Load State	mm
$P_{V,front}$ ($z_{V,load}$)	Tire Inflation Pressure Front Axle	bar
$P_{V,rear}$ ($z_{V,load}$)	Tire Inflation Pressure Rear Axle	bar

The load state is defined in the Calculation Task. In addition it is possible to define an additional mass for the load state empty so that it is possible to define every different weight of the vehicle.

Due to this different load states some dimensions of the vehicle are changing.

The distance of gravity center is the horizontal distance between the center of gravity and the front axle.

The height of gravity center is the vertical distance between the ground and the center of gravity.

And the height of the hitch is the vertical distance between the ground and the coupling point for the trailer.

If an additional mass is used the dimensions depending on the load state (distance and height of gravity center, height of hitch) will be interpolated between the given values.

Nominal Weight

$m_{V,min}$	Curb Weight	kg

The Curb weight is the weight of the empty vehicle including a full fuel tank.

$m_{V,zul}$	Gross Weight	kg

The Gross weight is the maximum admissible weight of the vehicle.

Air Coefficient

A_v	Frontal Area	m^2

The Frontal Area is the cross-sectional area of the vehicle that is used for the calculation of the air resistance. With the frontal area the influence of the size of the vehicle is considered.

$c_{V,w}$	Drag Coefficient	–

The Drag Coefficient is the factor of the air resistance that depends on the shape of the vehicle.

$c_{V,a,f}$	Lift Coefficient Front Axle	–
$c_{V,a,r}$	Lift Coefficient Rear Axle	–

The lift coefficients of the front and the rear axle consider the influence of the vehicle velocity on the wheel loads. Usually, the wheel loads are getting smaller with higher velocity. So a positive lift coefficient means that the wheel loads are decreasing. If the lift coefficients are negative then the wheel loads are increasing with increasing velocity.

The air resistance acts in the track surface. Therewith the horizontal air resistance has no influence on the wheel loads. To consider the effects of the different heights of the real acting point the lift coefficients of the axles have to be used.

Additional Aerodynamic Coefficients—Data Bus Dependent
Further option for modification of aerodynamic parameters (drag coefficient, lift coefficient front axle, and lift coefficient rear axle) which can be modified according to the Data Bus input value ‘x-axis for drag modification’:

that means opening and closing of aerodynamic spoiler as function of any Data Bus set value (with hysteresis).

Threshold Values

$\lambda_{V,ThresholdAscending}$	Threshold Value Ascending	–
$t_{V,ascending}$	Time interval of Parameter Modification—Ascending	s
$\lambda_{V,a,f}$	Threshold Value Descending	–
$t_{V,descending}$	Time interval of Parameter Modification—Descending	s

These inputs define the modification behavior of the aerodynamic coefficients during calculation. The ascending and descending hysteresis threshold values and the modification time interval have to be defined. The threshold values are related to the vehicle's Data Bus input 'x-axis for drag modification'. The unit of the threshold values can be defined by the user.

Aerodynamic Coefficients after Threshold

$c_{V,w,dataBusDep}$	Drag Coefficient	–
$c_{V,a,f,dataBusDep}$	Lift Coefficient Front Axle	–
$c_{V,a,r,dataBusDep}$	Lift Coefficient Rear Axle	–

In these table columns the values are defined which the aerodynamic coefficients will have at the end of the modification time interval.

Lateral Dynamics Vehicle

Chassis Data

$t_{front,rear}$	Track Width Front/Rear	mm
$C_{\alpha\text{-}front,rear}$	Axle Stiffness Front/Rear	N/°

Dependent on curvature radius the vehicle must generate lateral forces, which are impacted by the lateral acceleration. For calculation of the sideslip angle and thus the steering angle the stiffness of the front and rear axle is needed. For the calculation of the downforces of each wheel the track width is also needed.

Crosswind Force Data

$L_{vehicle}$	Total Length	m
$A_{Lateral}$	Vehicle Lateral Surface	m^2
l	Distance Vehicle Front End—Front Axle	m
c_S	Crosswind Force Coefficient	–
c_{MZ}	Yaw Moment Coefficient	–

The curvature radius is not only responsible for the lateral forces. If cornering is chosen, the influence of sidewind can be calculated. Dependent on the angle of approach the above subscripted values are recommended.

Drag Characteristic

$c_{V,w}(x)$	Drag Characteristic as function of a value from the Data bus	–

Cold Start Correction—Cycle Dependent

$z_{V,cold,1}$	Cycle Name 1	–
$c_{V,cold,1}(t)$	Cold Start Factor 1	–
$z_{V,cold,2}$	Cycle Name 2	–
$c_{V,cold,2}(t)$	Cold Start Factor 2	–
$z_{V,cold,3}$	Cycle Name 3	–
$c_{V,cold,3}(t)$	Cold Start Factor 3	–
$z_{V,cold,4}$	Cycle Name 4	–
$c_{V,cold,4}(t)$	Cold Start Factor 4	–
$z_{V,cold,5}$	Cycle Name 5	–
$c_{V,cold,5}(t)$	Cold Start Factor 5	–

If the switch *Drag Characteristic* is activated, the drag coefficient is interpolated from the Drag Characteristic, depending on the value of the Data Bus input x-axis for drag coefficient. This enables the user to define a drag coefficient, e.g. temperature dependent.

In addition to the possibility of calculating the higher fuel consumption based upon the higher friction mean pressure, while the engine is cold there is another possibility to consider the effects of a cold start. In the vehicle the cold start factors can be defined for different cycles as a function of time. If the cold start correction switch is activated the actual fuel consumption is always multiplied with this cold start factor and gives the higher fuel consumption.

Temperature Curves Cycle 1

$z_{V,temp,1}$	Cycle Name for Cycle 1	–
$T_{V,temp,1,i}(t)$	Temperature Curve 1,…,5 for Cycle 1	K

Here the time-dependent temperature characteristics for the 1st cycle are defined.

Temperature Curves Cycle 2

$z_{V,temp,2}$	Cycle Name for cycle 2	–
$T_{V,temp,2,i}(t)$	Temperature Curve 1,…,5 for Cycle 2	K

Here the time-dependent temperature characteristics for the 2nd cycle are defined.

Temperature Curves Cycle 3

$z_{V,temp,3}$	Cycle Name for Cycle 3	–
$T_{V,temp,3,i}(t)$	Temperature Curve 1,…,5 for Cycle 3	K

Here the time-dependent temperature characteristics for the 3rd cycle are defined.

Temperature Curves Cycle 4

$z_{V,temp,4}$	Cycle Name for Cycle 4	–
$T_{V,temp,4,i}(t)$	Temperature Curve 1,…,5 for a Cycle 4	K

Here the time-dependent temperature characteristics for the 4th cycle are defined.

Temperature Curves Cycle 5

$z_{V,temp,5}$	Cycle name for Cycle 5	–
$T_{V,temp,5,i}(t)$	Temperature Curve 1,…,5 for Cycle 5	K

Here the time-dependent temperature characteristics for the 5th cycle are defined.

Temperature Values—Cycle Independent

$T_{V,temp,5,i,cycleIndep}$	Temperature cycle independent 1,…,5	K

If one of the 'Temperature Curves Cycle 1–5' is used, a cycle independent temperature has to be defined for the case that further tasks (cycle independent) are performed or the assigned cycle is not available.

Resistance Function

$A_{V,res}$	Factor 1 of the Resistance Function (Constant Part)	N
$B_{V,res}$	Factor 1 of the Resistance Function (Linear Part)	Nh/km
$C_{V,res}$	Factor 1 of the Resistance Function (Quadratic Part)	Nh^2/km^2

In addition, the following data of the reference vehicle has to be defined:

$m_{V,ref}$	Weight of the Reference Vehicle	kg
$A_{V,ref}$	Frontal Area of the Reference Vehicle	m^2
$c_{V,w,ref}$	Drag Coefficient of the Reference Vehicle	–

The Resistance Function can also be converted from the Coasting Characteristic, see "Conversion from Coasting Characteristic to Resistance Function/Resistance Table."

Resistance Table

$F_{V,res}(v_V)$	Driving Resistance as function of vehicle velocity	N

In addition, the following data of the reference vehicle have to be defined:

$m_{V,ref}$	Weight	kg

The Resistance Table can also be converted from the coasting characteristic, see "Conversion from Coasting Characteristic to Resistance Function/Resistance Table."

Conversion from Coasting Characteristic to Resistance Function/Resistance Table

$v_{V,coasting}(t)$	Coasting Characteristic (vehicle velocity as function of time)	m/s
$trunc_{Vcoasting,left}$	Truncate left	%
$trunc_{Vcoasting,right}$	Truncate right	%

When the selection switch 'Driving Resistance' is set to 'Function with Reference Vehicle' or 'Characteristic with Reference Vehicle,' the option 'Driving Resistance from Coasting Characteristic' can be chosen. By selecting a conversion button (located at the coasting characteristic), the Resistance Function/Resistance Table is calculated using the values of the coasting characteristic.

Since the original coasting characteristic is often sensitive at the beginning of the measurement (small t) or at its end (small v) and these points have a big and sometimes negative influence on the resulting resistance parabola, there is a possibility to exclude the 'disturbing points' from certain intervals at the beginning or at the end of the characteristics (defined in the percentage of the whole domain, usually under 5 %) from the conversion. This is done by defining values for the fields 'Truncate left' and 'Truncate right'.

It is recommended to always accomplish the conversion into the Resistance Table first, adjust the 'excluded' intervals until the Resistance Table shows a satisfying pattern (without 'jumps' at its ends) and then, if needed, make the conversion into the parabola coefficients.

Conversion from Deceleration Interval Characteristic to Resistance Function/Resistance Table

$v_V(t)$	Coasting Characteristic (vehicle velocity as function of time)	m/s
$trunc_{Vdeceleration,left}$	Truncate left	%
$trunc_{Vdeceleration,right}$	Truncate right	%
$\Delta v_{Vdeceleration}(t)$	Velocity Interval	km/h

This feature converts the required values from the so-called 'Deceleration Interval Characteristic'; every input row of this characteristic defines the time for a

deceleration (e.g., velocity interval = 10 km/h) around a specified vehicle velocity. For example, the defined time at 120 km/h corresponds to the time needed for the vehicle to decelerate from 125 to 115 km/h. Similar to the conversion from Coasting Characteristic, there are options for 'Truncate left' and 'Truncate right' to cut off data which might have a bad influence on the conversion results. Additionally, there is an input field for the definition of the velocity interval.

2.1.3 Input and Output Variables

2.1.3.1 Mechanical Connections

s_V	Distance traveled from the start of the calculation	m
v_V	Velocity	m/s
a_V	Acceleration	m/s^2
F_V	Force at the vehicle	N

2.1.3.2 Data Input

$x_{V,drag}$	x-Axis For Drag Modification	–

2.1.3.3 Data Output

a_V	Acceleration	m/s^2
s_V	Distance	m
v_V	Velocity	m/s
$T_{V,temp,cycle,i}$	Temperature Curve 1,…,5 for Cycle i	K
P_V	Power	W
$P_{V,loss}$	Power Loss	W

2.1.4 Computation of the Module Variables

$m_{V,act}$	Instantaneous vehicle mass	kg
$h_{V,cog,act}$	Actual Height of Gravity Center	mm
$l_{V,cog,act}$	Actual Distance of Gravity Center	mm
$F_{V,air}$	Air drag force	N
$v_{U,V,rel}$	Relative wind velocity in vehicle direction	m/s
$F_{V,incl}$	Inclination resistance	N

(continued)

$F_{V,res}$	Resistance force	N
$F_{W,x,f,ax}$	Front axis load	N
$F_{W,x,r,ax}$	Rear axis load	N
$N_{W,f,r}$	Number of right front wheels	–
$N_{W,f,l}$	Number of left front wheels	–
$N_{W,r,r}$	Number of right rear wheels	–
$N_{W,r,l}$	Number of left rear wheels	–
F_A	Trailer Force	N
α_U	Actual Inclination $\alpha_U = \alpha_{U,up} + \alpha_{U,dn}$	rad
$F_{Lateral}$	Lateral force	N
F_{Wind}	Lateral force effected by crosswind	N
$F_{S,front(rear)}$	Lateral force on the axle front and rear	N
$\alpha_{Compass}$	Actual angle	rad
$\alpha_{f,r}$	Side slip angle front, rear	rad
δ	Steering angle	rad
β	Side slip angle vehicle	rad
D	Distance vehicle front—pressure point	m

2.1.5 Equation System

2.1.5.1 Instantaneous Vehicle Mass

For evaluating the forces, which are acting on the vehicle, the current load conditions are important. They are specified for each calculated task in two different ways.

(a) **Load conditions fixed as load stage** [2
The actual vehicle mass

$$m_{V,act} = m_V\left(z_{V,load}\right) \tag{2.1.1}$$

is determinate by interpolation between the three load stages [2]

$$\begin{aligned} &\text{empty:} \quad Z_{V,load} = 0 \rightarrow m_V(0) = m_{V,min} \\ &\text{half:} \quad Z_{V,load} = 1 \rightarrow m_V(1) = \frac{m_{V,min} + m_{V,zul}}{2} \\ &\text{full:} \quad Z_{V,load} = 2 \rightarrow m_V(2) = m_{V,zul} \end{aligned} \tag{2.1.2}$$

(b) **If an additional mass describes the load**
The instantaneous vehicle mass is evaluated as followed [2]

$$m_{\mathrm{V,act}} = m_{\mathrm{V}}(0) = m_{\mathrm{V,zul}} \tag{2.1.3}$$

2.1.5.2 Number of Wheels

The number of wheels $N_{\mathrm{W,f,r}}$, $N_{\mathrm{W,f,l}}$, $N_{\mathrm{W,r,r}}$ and $N_{\mathrm{W,r,l}}$ are determined by summation of all wheels in consideration of their wheel location $L_{\mathrm{W},i}$.

2.1.5.3 Position of the Total Center of Gravity

The location of acting point of mass forces is necessary for the allocation of the wheel loads.

We have to distinguish between:

(a) **For driving on road** [2]

$$h_{\mathrm{V,cog,act}} = h_{\mathrm{V,cog}}(Z_{\mathrm{V,load}}) \tag{2.1.4}$$

$$l_{\mathrm{V,cog,act}} = l_{\mathrm{V,cog}}(Z_{\mathrm{V,load}}) \tag{2.1.5}$$

The actual values for the height and the horizontal distance are determined by interpolation between the three load stages.

(b) **For the chassis dynamometer** [2]:

$$h_{\mathrm{V,cog,act}} = h_{\mathrm{V,cd}} \tag{2.1.6}$$

For calculations on a chassis dynamometer just the vertical distance of the actual gravity center and the support point are important.

2.1.5.4 Hitch Force

The force at the vehicle hitch is caused by the mass and resistance force of the trailer [2]

$$F_{\mathrm{A}} = m_{\mathrm{A,virt}} \cdot [a_{\mathrm{V}} + g \cdot \sin(\alpha_{\mathrm{U}})] + F_{\mathrm{A,virt}} \cdot \cos(\alpha_{\mathrm{U}}) \tag{2.1.7}$$

2.1.5.5 Dynamic Wheel Loads

Front Axis

The summation of all moments around the contact point between rear wheels and road has to be zero [2]:

$$\sum M_{\mathrm{r,ax}} = 0 \tag{2.1.8}$$

Out of this equation we can calculate the load of the front axis [2].

$$F_{\mathrm{w,x,f,ax}} = m_{\mathrm{V,act}} \left[\left(1 - \frac{l_{\mathrm{V,cog,act}}}{l_{\mathrm{V,fr}}} \right) \cdot g \cdot \cos \alpha_{\mathrm{U}} - \frac{h_{\mathrm{V,cog,act}}}{l_{\mathrm{V,fr}}} \cdot (a_{\mathrm{V}} + g \cdot \sin \alpha_{\mathrm{u}}) \right] - F_{\mathrm{V,lift,f}} \tag{2.1.9}$$

The load on the front axis is allocated proportionate onto the single front wheels for the right and the left side.

Right front wheel load [2]:

$$F_{\mathrm{W,x,f,r}} = \frac{F_{\mathrm{W,x,f,ax}}}{2 \cdot N_{\mathrm{W,f,r}}} \tag{2.1.10}$$

Left front wheel load [2]:

$$F_{\mathrm{W,x,f,l}} = \frac{F_{\mathrm{W,x,f,ax}}}{2 \cdot N_{\mathrm{W,f,l}}} \tag{2.1.11}$$

Rear Axis

The summation of all moments around the contact point between front wheels and road has to be zero [2]:

$$\sum M_{\mathrm{f,ax}} = 0 \tag{2.1.12}$$

From this equation we can calculate the load of the rear axis [2].

$$F_{\mathrm{w,x,r,ax}} = m_{\mathrm{V,act}} \left[\frac{l_{\mathrm{V,cog,act}} \cdot g \cdot \cos \alpha_{\mathrm{U}}}{l_{\mathrm{V,fr}}} + \frac{h_{\mathrm{C,cog,act}}}{l_{\mathrm{V,fr}}} \cdot (a_{\mathrm{V}} + g \cdot \sin \alpha_{\mathrm{U}}) \right] - F_{\mathrm{V,lift,r}} \tag{2.1.13}$$

The load on the rear axis is allocated proportionate onto the single rear wheels for the right and the left side.

Right rear wheel load [2]:

$$F_{W,x,r,r} = \frac{F_{W,x,r,ax}}{N_{W,r,r}} \tag{2.1.14}$$

Left rear wheel load [2]:

$$F_{W,x,r,l} = \frac{F_{W,x,r,ax}}{N_{W,r,l}} \tag{2.1.15}$$

2.1.5.6 Resistance Forces

(a) **from physical units**
The force of resistance is the addition of the air drag force and the longitudinal force caused by the road inclination. The rolling resistance is calculated separately for all wheels.
Air Drag [2]

$$v_{U,V,rel} = v_V + v_{U,air} \tag{2.1.16}$$

$$F_{V,air} = -0.5 \cdot c_w \cdot A_v \cdot \rho_{U,air} \cdot v_{U,V,rel}^2 \tag{2.1.17}$$

Inclination Resistance [2]

$$\alpha_U = \alpha_{U,up} + \alpha_{U,dn} \tag{2.1.18}$$

$$F_{V,incl} = m_{v,act} \cdot g \cdot \sin \alpha_U \tag{2.1.19}$$

Additional traction or pushing forces are taken into account with the relative forces $k_{V,add,trac}$ and $k_{V,add,push}$. They are related to the weight of the vehicle and their size is fixed by the equation solver for special Calculation Tasks (e.g., Max Traction Force).
Summation [2]

$$F_{V,res} = F_{V,air} + F_{V,incl} + \left(k_{v,add,trac} + k_{v,add,push}\right) \cdot m_{V,act} \cdot g \tag{2.1.20}$$

(a) **from Resistance Function with reference vehicle**
The parameters c_A, c_B, and c_C are entered. Out of these values the driving resistance function can be defined as followed [2]:

$$F_{\mathrm{V,res}} = \frac{m_{\mathrm{act}}}{m_{\mathrm{ref}}} \cdot c_{\mathrm{A}} + \frac{m_{\mathrm{act}}}{m_{\mathrm{ref}}} \cdot c_{\mathrm{B}} \cdot v_{\mathrm{V}} + \frac{c_{\mathrm{W}} \cdot A}{c_{\mathrm{W,ref}} \cdot A_{\mathrm{ref}}} \cdot c_{\mathrm{C}} \cdot v_{\mathrm{V}}^2 \tag{2.1.21}$$

(b) **from Resistance Table with reference vehicle**
The driving resistance curve is defined as force versus vehicle velocity. From this table the constant and proportional part can be evaluated.
For the reference vehicle mass can be calculated [2]:

$$F(v) = A + B \cdot v_{\mathrm{V}} + \bar{F}(v_{\mathrm{V}}) \tag{2.1.22}$$

$$\text{for} \quad v_{\mathrm{V}} = 0 \rightarrow A = F(v_{\mathrm{V}} = 0) \tag{2.1.23}$$

$$B = F'(v_{\mathrm{V}} = 0) \tag{2.1.24}$$

These parts are related to the actual vehicle mass and they can be handled separately.
The function part of higher order is calculated [2]:

$$\bar{F}(v_{\mathrm{V}}) = F(v_{\mathrm{V}}) - A - B \cdot v_{\mathrm{V}} \tag{2.1.25}$$

Now the actual resistance force can be evaluated for each time step [2]:

$$F_{\mathrm{V,res}} = \frac{m_{\mathrm{act}}}{m_{\mathrm{ref}}} \cdot (A + B \cdot v_{\mathrm{V}}) + \bar{F}(v_{\mathrm{V}}) \tag{2.1.26}$$

$$F_{\mathrm{V,res,ges}} = F_{\mathrm{V,res}} + F_{\mathrm{V,incl}} + \left(k_{v,\mathrm{add,trac}} + k_{v,\mathrm{add,push}}\right) \cdot m_{\mathrm{V,act}} \cdot g \tag{2.1.27}$$

(c) **from Resistance Function without reference vehicle**
The parameters c_{A}, c_{B}, and c_{C} are entered. Out of these values the driving resistance function can be defined as followed [2]:

$$F_{\mathrm{V,res}} = c_{\mathrm{A}} + c_{\mathrm{B}} \cdot v_{\mathrm{V}} + c_{\mathrm{C}} \cdot v_{\mathrm{V}}^2 \tag{2.1.28}$$

(d) **from Resistance Table without reference vehicle**
The driving resistance curve is defined as force versus vehicle velocity. From this table the constant and proportional part can be evaluated [2].

$$F(v) = A + B \cdot v_{\mathrm{V}} + \bar{F}(v_{\mathrm{V}}) \tag{2.1.29}$$

$$\text{for} \quad v_{\mathrm{V}} = 0 \rightarrow A = F(v_{\mathrm{V}} = 0) \tag{2.1.30}$$

$$B = F'(v_{\mathrm{V}} = 0) \tag{2.1.31}$$

These parts are related to the actual vehicle mass and they can be handled separately.

The function part of higher order is calculated [2]:

$$\bar{F}(v_{\mathrm{V}}) = F(v_{\mathrm{V}}) - A - B \cdot v_{\mathrm{V}} \tag{2.1.32}$$

Now the actual resistance force can be evaluated for each time step [2]:

$$F_{\mathrm{V,res}} = (A + B \cdot v_{\mathrm{V}}) + \bar{F}(v_{\mathrm{V}}) \tag{2.1.33}$$

$$F_{\mathrm{V,res,ges}} = F_{\mathrm{V,res}} + F_{\mathrm{V,incl}} + \left(k_{v,\mathrm{add,trac}} + k_{v,\mathrm{add,push}}\right) \cdot m_{\mathrm{V,act}} \cdot g \tag{2.1.34}$$

2.1.5.7 Conversion from Coasting Characteristic to Resistance Function/Resistance Table

After derivation and t-variable substitution, the coasting characteristic $v = f(t)$ is transferred to the characteristic $a = f(v)$.

Multiplying the characteristic with the vehicle mass, the resistance characteristic $F = f(v)$ is obtained.

This characteristic is approximated with a parabola $F = A + B \cdot v + C \cdot v^2$ using the least square method.

2.1.5.8 Lateral Force

For the calculation of cornering there are some restrictions:

- Steady state cornering
- Linearization for small angle
- Linear approach for lateral forces
- No changes of the gravity center
- Wheels of the axle assembled at the axle middle
- No influence between lateral and radial forces

With the following points the parameters of cornering are calculated:

(1) The sum of the lateral forces are [2]:

$$F_{\text{lateral}} = F_{\text{s},\rho} + F_{\text{s,wind}} + F_{\text{s},\beta} \tag{2.1.35}$$

The single parts of the lateral forces can be calculated by the following formulas:
Front (rear) axle force by lateral acceleration [2]:

$$F_{\text{front(rear)},\text{lateral},\rho} = \frac{m_{\text{Vehicle}} \cdot v_{\text{Vehicle}}^2}{\rho} \cdot \frac{N_{\text{front(rear)}}}{N_{\text{Vehicle}}} \tag{2.1.36}$$

If required, the lateral force influence by wind can be computed by [2]:

$$F_{\text{s,Wind}} = c_{\text{s}} \cdot \rho \cdot \left(\frac{v_{\text{Wind}}^2}{2}\right) \cdot A_{\text{S}} \cdot \sin\left(\alpha_{\text{Compass}} + \beta_{\text{slip}}\right) \tag{2.1.37}$$

The angle α_{Compass} is the angle of the vehicle since starting (which could change). The start value can be chosen under *Wind Velocity*.
Lateral force influence by sideslip angle [2].

$$F_{\text{s},\beta} = c_{\text{s}} \cdot \rho \cdot \left(\frac{v_{\text{Vehicle}}^2}{2}\right) \cdot A_{\text{S}} \cdot \sin\left(\beta_{\text{slip}}\right) \tag{2.1.38}$$

The pressure point of the crosswind is important for the splitting on the axles of crosswind force. It is measured from the front of the vehicle [2].

$$d_{\text{lateral}} = l \cdot \frac{c_{\text{MZ}}}{c_{\text{s}}} \tag{2.1.39}$$

Front axle lateral force by crosswind [2]:

$$F_{\text{S,front}} = \frac{d_{\text{lateral}} - l_{\text{front,frontaxle}}}{b_{\text{wheelbase}}} \cdot \left(F_{\text{s,Wind}} + F_{\text{s},\beta}\right) \tag{2.1.40}$$

Rear axle lateral force by crosswind [2]:

$$F_{\text{S,rear}} = \frac{b_{\text{wheelbase}} - d_{\text{lateral}} + l_{\text{front,frontaxle}}}{b_{\text{wheelbase}}} \cdot \left(F_{\text{s,Wind}} + F_{\text{s},\beta}\right) \tag{2.1.41}$$

(2) The change of downforces of each under influence of the curvature.
The summation of all moments around the contact point between right (left) wheels and road has to be zero [2]:

$$\sum M_{\text{f,(r),ax}} = 0 \tag{2.1.42}$$

Downforce wheel right (left) front [2]:

$$F_{\mathrm{D,f,r(l)}} = F_{\mathrm{D,f,r(l)}} - (+)\frac{h_{\mathrm{GC}}}{t_{\mathrm{f}}} \cdot F_{\mathrm{S,front}} \tag{2.1.43}$$

Downforce wheel right (left) rear [2]:

$$F_{\mathrm{D,r,r(l)}} = F_{\mathrm{D,r,r(l)}} - (+)\frac{h_{\mathrm{GC}}}{t_{\mathrm{r}}} \cdot F_{\mathrm{S,rear}} \tag{2.1.44}$$

(3) Sideslip angel front (rear) under the influence of the radial force [2]:

$$\alpha_{\mathrm{f(r)}} = \frac{\frac{F_{\mathrm{S,f(r)}}}{c_\alpha}}{1 + \frac{F_{\mathrm{radial,f(r)}}}{c_\alpha}} \tag{2.1.45}$$

(4) Ackermann angle [2]:

$$\alpha_{\mathrm{ackermann}} = \frac{b_{\mathrm{Wheelbase}}}{\rho} \tag{2.1.46}$$

(5) Steering angle [2]:

$$\delta = \frac{\alpha_{\mathrm{ackermann}}}{1 + \frac{F_{\mathrm{radial,f}}}{c_\alpha}} + \alpha_{\mathrm{f}} - \alpha_{\mathrm{r}} \tag{2.1.47}$$

(6) Slip angle [2]:

$$\beta = \frac{b_{\mathrm{wheelbase}} \cdot l_{\mathrm{GC}}}{\delta} - \alpha_{\mathrm{r}} \tag{2.1.48}$$

2.2 Clutch (C)

Stationary idle, transition to motion and interruption of the power flow are all made possible by the clutch. The clutch slips to compensate for the difference in the rotational speeds of engine and drivetrain when the vehicle is set in motion. When a change in operation conditions makes it necessary to change gears, the clutch disengages the engine from the drivetrain for the duration of the procedure.

The clutch contains a model for a friction clutch as it is used in cars with manual gearboxes. In this case the clutch is controlled by the driver via the cockpit [1].

The last possibility of using the clutch is together with a CVT gearbox. There it is only necessary for starting. In this case the clutch is controlled by the control module CVT control [1].

2.2.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Model
simple
detailed
For the simple model of the clutch the maximum transferable torque has to be defined.

Selection Button Model
simple
detailed
At the detailed model of the clutch the transferable torque is derived from the geometric data of the clutch as well as from the friction characteristic.

Selection Button Control Variable
Desired Clutch Release
Desired Torque
This is the 'usual' selection where the clutch gets the value of the desired clutch release. Therefore, the Data Bus input *Desired Clutch Release* has to be connected.

Selection Button Control Variable
Desired Clutch Release

Desired Torque
This mode considers the desired torque to be transmitted. Therefore, the Data Bus input.

Torque Demand has to be connected.

Switch Dynamic Mode
If this switch is activated the clutch calculation always stays dynamic and never switches to a kinematic connection.

Switch Free Definable Friction Characteristic
If this switch is activated and depending on whether 'simple' or 'detailed' model has been chosen, the characteristic 'Maximum Transferable Torque' overslip, or the characteristic 'Friction Coefficient' overslip can be defined.

2.2.2 User-Defined Variables

$r_{C,I}$	Inner Radius	mm
$r_{C,o}$	Outer Radius	mm

With these values the mean radius of the clutch is calculated.

N_c	Number of Sets of Frictional Surfaces	–

The number of sets of frictional surfaces is equal to the number of the clutch disks. In the calculation every disk is set with two frictional surfaces.

$\mu_{C,fric}$	Friction Coefficient sticking	–
$\kappa_{C,fric}$	Friction Coefficient Ratio slipping/sticking	–
$P_{C,fric}$	Form Parameter	rad/s

From these values the friction characteristic of the clutch is determined. The input of the two friction coefficients is only necessary if the switch 'Free definable Friction Characteristic' is deactivated (Fig. 2.3).

$\theta_{C,in}$	Inertia Moment on the drive side	kg m^2
$\theta_{C,out}$	Inertia Moment on the power take-off side	kg m^2
$M_{C,max}$	Maximum Transferable Torque	Nm

The maximum transferable torque is the maximum torque the clutch can transfer between the drive and the power take-off side. Its input is only necessary if the switch 'Free definable Friction Characteristic' is deactivated.

Pressure Force

$F_c(s_c)$	Pressure Force as a Function of the Clutch Release	N

The pressure force is the axial force the frictional surfaces are pressed together. This pressure force depends on the clutch release. With the pressure force it is possible to calculate the transmitted torque by considering the dimensions.

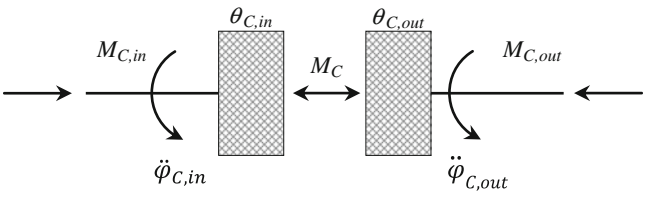


Fig. 2.3 Friction clutch model [2]

$M_{C,max}(\dot{\varphi}_{c,rel})$	Maximum Transferable Torque overslip	–

This characteristic is only required if the selection button 'model' is set to 'simple' and the switch 'Free definable Friction Characteristic' is activated.

$\mu_C(\dot{\varphi}_{c,rel})$	Friction Coefficient over slip	–

This characteristic is only required if the selection button 'model' is set to 'detailed' and the switch 'Free definable Friction Characteristic' is activated.

2.2.3 Input and Output Variables

2.2.3.1 Mechanical Connection

$\dot{\varphi}_{C,in}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{C,in}$	Angular acceleration on the drive side	rad/s^2
$\dot{\varphi}_{C,out}$	Angular velocity on the power take-off side	rad/s
$\ddot{\varphi}_{C,out}$	Angular acceleration on the power take-off side	rad/s^2
$M_{C,in}$	Torque on the drive side	Nm
$M_{C,out}$	Torque on the power take-off side	Nm

2.2.3.2 Data Input

$S_{C,act}$	Desired Clutch Release	–
$M_{C,desired}$	Desired Torque	Nm

2.2.3.3 Data Output

$S_{C,act}$	Actual Clutch Release	–
M_C	Clutch Torque	Nm
$\dot{\varphi}_{C,in}$	Input Speed	rad/s
$\dot{\varphi}_{C,out}$	Output Speed	rad/s
$P_{C,in}$	Input Power	W
$P_{C,out}$	Output Power	W
$P_{C,loss}$	Power Loss	W

2.2.4 Computation Variables

$\dot{\varphi}_{C,rel}$	Relative speed of the clutch	rad/s
$\mu_{C,st}$	Stick Friction Coefficient	–
$\mu_{C,sl}$	Slip friction coefficient	–
C_C	Friction gradient	–
$\mu_{c,act}$	Actual friction coefficient	–
$F_{C,act}$	Actual clamping force	N
M_C	Transmitted torque	Nm

2.2.5 Equation System

Friction Coefficient
Friction coefficient has to be evaluated for stick and slid friction. Which value is taken in consideration depends on the circumstances that the clutch is locked or unlocked.

They are fixed in the code with the following values:

$$\begin{aligned} \mu_{C,st} &= 0.4 && \text{friction coefficient sticking} \\ \mu_{C,sl} &= \mu_{C,st} \cdot 0.8 && \text{friction coefficient slipping} \end{aligned}$$

Mean effective radius of the clutch
The mean effective radius is the fictive radius, in which the friction force is acting [2]:

$$r_{C,m} = \frac{M_{C,max}}{N_C \cdot \mu_{C,st} \cdot F_C} \tag{2.2.1}$$

Actual friction coefficient
The relative speed between clutch in and out is determined [2].

$$\dot{\varphi}_{C,rel} = \dot{\varphi}_{C,in} - \dot{\varphi}_{C,out} \tag{2.2.2}$$

The friction gradient is also fixed in the code for typical conditions:

$$C_C = 0.01$$

The actual friction coefficient is calculated by using the following formula [2]:

$$\mu_{C,act} = \mu_{C,sl} + \left(\mu_{C,st} - \mu_{C,sl}\right) \cdot e^{\left(-\frac{\left|\dot{\varphi}_{c,rel}\right| \cdot C_C}{\mu_{c,st} - \mu_{c,sl}}\right)} \tag{2.2.3}$$

Actual Clamping force
Evaluation of the actual clamping force $F_{C,act}$ by interpolating out of the map $F_c(S_c)$ for the actual clutch release.

Transmitted Torque M_C
The transmitted torque is the torque value which goes through the clutch from the into the outside.

For the sliding clutch it is the possible moment limited by the friction [2]:

$$M_C = -\mu_{C,act} \cdot r_{C,m} \cdot F_{C,act} \cdot N_C \tag{2.2.4}$$

For the adhering clutch the clutch torque is determinate by the value which is applied by the system [2]:

$$M_C = \left| M_{C,in} - M_{C,out} \right| \tag{2.2.5}$$

Detection of sliding and adhesion
The clutch will slide as long these conditions are fulfilled:

$$\left[\left| M_{C,in} - M_{C,out} \right| \geq |M_C| \right] \vee \left[\dot{\varphi}_{C,rel} > 0 \right] \vee \left[S_{C,art} > 0.8 \right] \tag{2.2.6}$$

The clutch will adhere for the following condition

$$\left[\left| M_{C,in} - M_{C,out} \right| < |M_C| \right] \wedge \left[\dot{\varphi}_{C,rel} < 0.01 \right] \wedge \left[S_{C,act} < 0.8 \right] \tag{2.2.7}$$

2.3 Torque Converter (T)

Torque converters employ the force represented by a moving fluid to transmit engine torque. Because these devices compensate for differences in the rotating speeds of engine and drivetrain, they are ideal for effecting the transition from stationary to mobile operation. The torque converter also multiplies torque. First an impeller (pump) converts the mechanical energy emanating from the power unit into fluid energy (hydraulic fluid—ATF—is the preferred medium); a second transformation, back into mechanical energy, occurs at the blades within the turbine [1].

Among the benefits offered by torque converters are the following attributes: infinitely variable, stepless variations in torque and rpm, vibration insulation, absorption of torque peaks, and virtually wear-free power transfer [1].

These devices offer economical operation when used together with mechanical variable-ratio transmissions; operation with nonpositive engagement (slip) is limited in the interests of efficiency [1].

The converter contains a model for a torque converter as it is, e.g., used in vehicles with automatic gearboxes. For computing the output variables, the various characteristic curves of the converter are used. The characteristic curves are usually

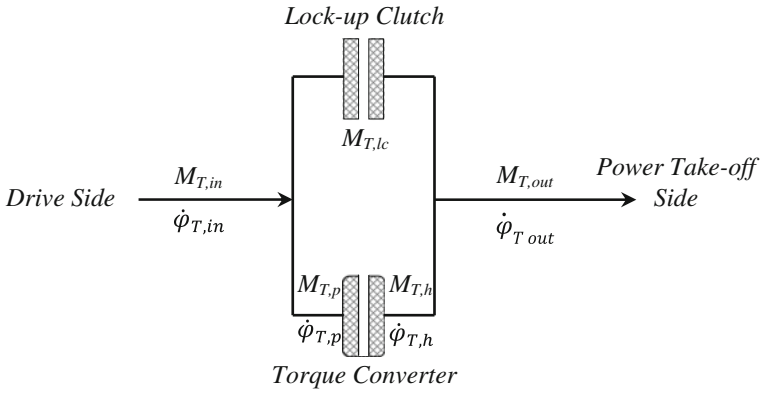


Fig. 2.4 Torque Converter with lock-up clutch model [2]

stationary. Normally, the deviation from dynamic characteristic curves is minor. If dynamic characteristic curves are known, they may be used [1].

The component torque converter also contains a lock-up clutch (Fig. 2.4). This lock-up clutch is in parallel to the torque converter and serves for lower losses in the torque converter because the slip is suppressed. The lock-up clutch has to be controlled by the control module clutch control [1].

2.3.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Switch Use for Reference
At the task Climbing Performance the maximum gradients are only calculated for the coupling part (torque multiplication equals zero). If more than one torque converter is in the model, the reference torque converter has to be determined with this switch. This means that from this torque converter the coupling part is determined, for which the gradients are calculated.

Selection Button Lock-up Friction Model
Linear
Simple
In this case the 'default' model is used: the maximum transferable torque of the lock-up clutch is calculated linearly through the clutch release value.

Selection Button Lock-up Friction Model
Linear
Simple
In this case the friction model of the clutch component is used.

2.3.2 User-Defined Variables

Selection Button Input options
Torque Conversion
Cf-Curve
K-Curve
In this case, the pump torque has to be defined as a function of the speed ratio at reference speed.

Selection Button Input options
Torque Conversion
Cf-Curve
K-Curve
In this case, the Cf-values have to be defined as a function of the speed ratio.

Selection Button Input options
Torque Conversion
Cf-Curve
K-Curve
In this case, the K-factors have to be defined as a function of the speed ratio.

$\theta_{T,p,oil}$	Inertia Moment of the Pump (with oil share)	kg m^2
$\theta_{T,h,oil}$	Inertia Moment of the Turbine (with oil share)	kg m^2

The mass moments of inertia of the pump and the turbine side are given with the oil share.

$\dot{\varphi}_{T,p,n}$	Reference Speed	rad/s

The reference angular velocity is the speed where the table for the torque conversion is measured. Reference speed means that throughout the whole measuring process the pump speed was fixed at this special reference angular velocity. For other pump speeds the corresponding values are extrapolated.

$M_{T,lock\text{-}up,max}$	Maximum Torque Lock-up Clutch	Nm

The maximum lock-up torque is the maximum torque that can be transferred via the lock-up clutch.

This torque can be transferred if the clutch is completely closed. If the clutch is closed partly (controlled operation; refer to component *Clutch Program* (CP) for more information), a correspondingly lower torque can be transferred.

Torque Conversion

$i_{T,Tor}(i_{T,Sp})$	Torque Ratio as a function of the Speed Ratio at Reference Speed	–

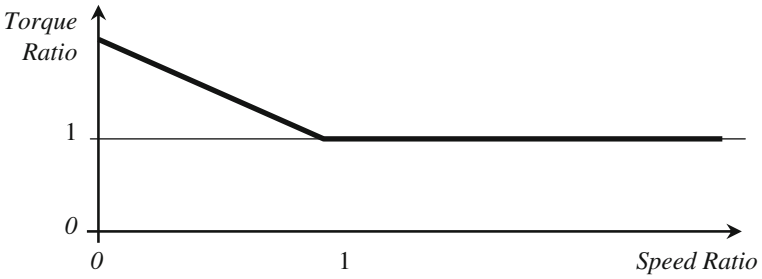


Fig. 2.5 Torque Ratio as function of the speed ratio [2]

The torque ratio is the division between the turbine torque and the pump torque. It depends on the speed ratio which is the division between the turbine and the pump speed. The torque ratio is nearly one throughout the whole speed ratio. Only when the speed ratio is nearly zero the torque ratio is increasing (refer to Fig. 2.5).

Torque Curve

$M_{T,Pump}(i_{T,Sp})$	Pump Torque as a function of the Speed Ratio at Reference Speed	Nm

These values are required when the selection button **Input options** is set to torque curve. The pump torque is the transferable torque between the pump and the turbine. It is a function of the speed ratio. At the speed ratio one, i.e., there is no difference in speed between the pump and the turbine, the pump torque is zero. If the speed ratio is between zero and one (the pump drives the turbine), the pump torque is positive. If the speed ratio is above one (the turbine drives the pump), the pump torque is negative.

In addition, there is a dependence on the ratio between the pump speed and the reference speed. This is calculated in the following way [2]:

$$M_{T,Pump,act} = M_{T,Pump} \cdot \left(\frac{\dot{\varphi}_{T,Pump}}{\dot{\varphi}_{T,P,n}} \right)^2 \tag{2.3.1}$$

$M_{T,Pump,act}$ Transferable Torque at the actual pump speed
$\dot{\varphi}_{T,Pump}$ Actual Pump Speed

Cf-Curve

$i_{T,Tor}$ (i_T)	Torque Ratio as a function of the Speed Ratio	–
Cf_T (i_T)	Cf-Values as a function of the Speed Ratio	kp.m.10^6/(1/min)^2

These values are required when the selection button **Input options** is set to *Cf-Curve*. In the calculation core, the Cf-values are converted to the pump torque assuming the reference speed as being 2000 rpm.

The relation between the Cf-values and the pump torque at reference speed is described by the following equation [2]:

$$Cf_T = \frac{M_{T,Pump,act} \cdot 10^6}{\dot{\varphi}^2_{T,Pump}} \tag{2.3.2}$$

K-Curve

$i_{T,Tor}$ (i_T)	Torque Ratio as a function of the Speed Ratio	–
K_T (i_T)	K-Values as a function of the Speed Ratio	(1/min)/Nm$^{0.5}$

These values are required when the selection button **Input options** is set to *K-Curve*. In the calculation core, the K-factors are converted to the pump torque assuming the reference speed is 2000 rpm.

The relation between the K-factors and the pump torque at reference speed is described by the following equation [2]:

$$K_T = \frac{\dot{\varphi}_{T,Pump}}{\sqrt{M_{T,Pump,act}}} \tag{2.3.3}$$

The K-values can only be positive (due to their definition). AVL CRUISE calculates pump torque for speed ratios above 1 by mirroring the pump torque around the point (1/0) in the speed ratio—pump torque—plane.

2.3.3 Input and Output Variables

2.3.3.1 Mechanical Connection

$\dot{\varphi}_{T,in}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{T,in}$	Angular acceleration on the drive side	rad/s^2
$\dot{\varphi}_{T,out}$	Angular velocity on the power take-off side	rad/s
$\ddot{\varphi}_{T,out}$	Angular acceleration on the power take-off side	rad/s^2
$M_{T,in}$	Input torque	Nm
$M_{T,out}$	Output torque	Nm

2.3.3.2 Data Input

Z_T	Desired Clutch Release	–
C_T	Modification of Torque Multiplication	–

2.3.3.3 Data Output

$M_{T,clutch,act}$	Clutch Torque	Nm
$\dot{\varphi}_{T,Pump}$	Pump Speed	rad/s
$M_{T,pump,act}$	Pump Torque	Nm
$\dot{\varphi}_{T,turb}$	Turbine Speed	rad/s
$M_{T,turb,act}$	Turbine Torque	Nm
$\dot{\varphi}_{T,Mp2000}$	Mp2000 (Pump torque at pump speed 2000)	Nm
$\ddot{\varphi}_{T,in}$	Pump Acceleration	rad/s^2
$\ddot{\varphi}_{T,out}$	Turbine Acceleration	rad/s^2
$\nu_{T,act}$	Speed Conversion	–
$\mu_{T,act}$	Torque Conversion	–
$P_{T,in}$	Pump Power	W
$P_{T,out}$	Turbine Power	W
$P_{T,loss}$	Power Loss	W

2.3.4 Computation Variables

$\dot{\varphi}_{T,rel}$	Difference of angular velocities between in and off side	rad/s
$K_{T,scale}$	Scale factor	–
$\nu_{T,act}$	Instantaneous speed conversion	–
$\mu_{T,act}$	Instantaneous torque conversion	–
$M_{T,pump,nom}$	Pump torque at nominal pump speed	Nm
$M_{T,pum,actp}$	Actual pump torque	Nm
$M_{T,turbin,acte}$	Actual turbine torque	Nm
$M_{T,clutch,act}$	Actual clutch torque (lockup)	Nm
$M_{T,trans}$	Transmittable torque of the converter with lock-up clutch on the pump side	Nm

2.3.5 Equation System

2.3.5.1 Converter Torque

The torque on the converter input and output depends on the speed ratio between pump and turbine as well on the absolute angular velocity of the pump.

Speed Ratio
This is the difference between the angular velocities of the clutch input and output side.

The actual speed ratio is evaluated:

(1) For pump speed is zero $\dot{\varphi}_{\mathrm{T,in}} = 0$ [2]:

(a) $(\dot{\varphi}_{\mathrm{T,out}} < 0)$

$$v_{\mathrm{T,act}} = i_{\mathrm{T,Tor}}(1) \tag{2.3.4}$$

(b) $(\dot{\varphi}_{\mathrm{T,out}} > 0)$

$$v_{\mathrm{T,act}} = i_{\mathrm{T,Tor}}(\max) \tag{2.3.5}$$

(c) $(\dot{\varphi}_{\mathrm{T,out}} = 0)$

$$v_{\mathrm{T,act}} = 1 \tag{2.3.6}$$

(2) With an input speed not equal zero $\left(\dot{\varphi}_{\mathrm{T,in}} \neq 0\right)$ [2]:

$$v_{\mathrm{T,act}} = \frac{\dot{\varphi}_{\mathrm{T,out}}}{\dot{\varphi}_{\mathrm{T,in}}} \tag{2.3.7}$$

Pump Torque
Now the transferable torque can be evaluated with a liner interpolation for the pump torque map [2]:

$$M_{\mathrm{T,pump,nom}} = M_{\mathrm{T,pump}}\left(v_{\mathrm{T,act}}\right) \tag{2.3.8}$$

The scale factor $K_{\mathrm{T,scale}}$ is for transformation from the nominal pump to the actual pump speed [2]:

$$K_{\mathrm{T,scale}} = \frac{\dot{\varphi}_{\mathrm{T,in}}}{\dot{\varphi}_{\mathrm{T,p,n}}} \tag{2.3.9}$$

The transformation is done in the following way [2]:

$$M_{\mathrm{T,pump,act}} = M_{\mathrm{T,pump,nom}} \cdot K_{\mathrm{T,scale}}^2 \tag{2.3.10}$$

Turbine Torque
With a linear interpolation in the torque ratio map we evaluate the actual torque ratio between pump and turbine [2]:

$$\mu_{\mathrm{T,act}} = C_T \cdot \left(i_{\mathrm{T,Tor}}\left(v_{\mathrm{T,act}}\right) - 1\right) + 1 \tag{2.3.11}$$

The actual turbine torque is determinate by the formula [2]:

$$M_{\mathrm{T,turb,act}} = M_{\mathrm{T,pump,act}} \cdot \mu_{\mathrm{T,act}} \tag{2.3.12}$$

Clutch Torque
The clutch torque is the transmitted torque of the lock-up clutch. If the lock-up clutch is acting the whole transmitted torque is split into the pump-turbine part and the clutch part. The size of the transmittable clutch torque depends linear on the clutch release [2].

$$M_{\mathrm{T,clutch,act}} = M_{\mathrm{T,clutch,max}} \cdot Z_{\mathrm{T}} \tag{2.3.13}$$

Transmittable Torque
The transmittable torque of the converter is the summation of the actual pump and the clutch torque [2].

$$M_{\mathrm{T,trans}} = M_{\mathrm{T,pump,act}} + M_{\mathrm{T,clutch,act}} \tag{2.3.14}$$

Detection of locked or unlocked clutch
The lock-up clutch will slide as long these conditions are fulfilled [2]:

$$\left[\left|M_{\mathrm{T,in}} - M_{\mathrm{T,out}}\right| \geq |M_{\mathrm{T}}|\right] \nabla \left[\dot{\varphi}_{\mathrm{T,rel}} > 0\right] \vee \left[S_{\mathrm{T,act}} > 0.8\right] \tag{2.3.15}$$

The clutch will adhere for the following condition [2]:

$$\left[\left|M_{\mathrm{T,in}} - M_{\mathrm{T,out}}\right| < |M_{\mathrm{T}}|\right] \Delta \left[\dot{\varphi}_{\mathrm{T,rel}} < 0.01\right] \wedge \left[S_{\mathrm{T,act}} < 0.8\right] \tag{2.3.16}$$

2.4 Gearbox (G)

Gear transmissions featuring several fixed ratios can maintain a correspondence between the respective performance curves for engine and vehicle. The correspondence with the hyperbola for maximum engine output will be acceptable or indeed quite good, depending upon a multiplicity of factors including the number of

available gears, the spacing of the individual ratios within the required conversion range and the engine's full load torque curve [1].

The component *Gearbox* contains a model for a gearbox with different gear steps. You can define as many gears as you want. For every gear it is possible to define the transmission ratio, the mass moments of inertia, and the moment of loss [1].

In the component for manual gearboxes, the engine torque will be turned into a power take-off torque by considering the transmission, the mass moments of inertia, and the moment of loss [1].

The gearbox can be used for a manual or automatic gearbox. When used as an automatic gearbox, the gear shifting process will be controlled by the control module gearbox control or gearbox program. The driver will do this task when used as a manual gearbox [1].

2.4.1 Properties

Switch Variation
The gearbox can be given free for variation with this switch. For the gearbox, the transmission ratio can be changed by multiplication with an additional factor. The setup of the variation parameters is done in the folder.

Switch Output
If this switch is activated a result output for this component is made.

Switch Gear Shift Time
If this switch is activated, the map for the gear shift times is used during calculation.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map temperature dependent
In this case no losses are calculated in the gearbox.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map temperature dependent

In this case, the losses are calculated by a constant efficiency which only depends on the gear position.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map temperature dependent

In this case, the losses are calculated by the efficiency which only depends on the gear position and by a torque loss map which depends on the gear position and the drive speed.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map temperature dependent

In this case the losses are interpolated out of a torque loss map, which depends on the gear position, the drive speed, and the drive torque. At the torque and speed division a special approximation of the maps is made by cutting through the map at the defined torque and speed values.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map temperature dependent

In this case, the losses are calculated with the usage of up to 5 torque loss maps *Gear Losses Temperature Dependent* where each map is associated with a user-defined constant temperature value. An interpolation between these maps is done so that for every time step a torque loss can be generated.

The temperature used in the calculation comes through the Data Bus input *Temperature* of the component *Gearbox*. For example, it could be connected with one of the up to 5 cycle-dependent temperature characteristics in the component *Vehicle*.

Selection Button Gear Shifting Losses
Deactivated
Efficiency
In this case, no gear shifting losses are calculated.
Selection Button Gear Shifting Losses
Deactivated
Efficiency
When this option is activated, the efficiencies for upshifting and for downshifting have to be defined for every gear. With this information the losses during the shifting processes are calculated. *This is only done for Automatic Transmission Models.*

Switch Torque Loss Correction Temperature Dependent
Here a temperature-dependent torque loss map can be activated.

Switch Efficiency Map (for Torque Loss Maps)
When this switch is activated, the efficiency can be entered in a separate table instead of the torque loss. After pushing the button *Conversion Efficiency in Torque Loss,* the torque loss map is created automatically.

Switches Torque Loss Map 1, …, 5
With these switches, for up to 5 temperature levels the associated loss maps can be activated. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition
Deactivated
Torque Partition
Torque and Speed Partition
In this case no partition of torque or speed is done. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition
Deactivated
Torque Partition
Torque and Speed Partition
In this case a torque partition is done. A special approximation of the maps is made by cutting through the map at the defined torque values. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition
Deactivated
Torque Partition
Torque and Speed Partition
In this case a torque and speed partition is done. A special approximation of the maps is made by cutting through the map at the defined torque and speed values.

This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Table Numerical Values of the Torque Loss Partition
For the torque and the speed range the borders for activation and deactivation can be defined here. The values are defined in percentage of the maximum torque and speed values.

2.4.2 User-Defined Variables

Gear Ratio Table

N_G	Gear Position	–

The input stands for the gear number (1 for 1st gear, 2 for 2nd gear,…). Zero means the neutral gear. It has always the transmission one. This neutral gear is needed to consider the mass moments of inertia when the vehicle is only rolling. The program determines the number of gear steps automatically.

$i_G[N_G]$	Transmission Ratios in the single gear steps	–

The transmissions can be defined for the different gear positions. However the transmission for the neutral gear (gear position 0) has to be 1. If the number of teeth is defined, the transmission ratio of each gear step is automatically determined.

$\Theta_{G,in}[N_G]$	Inertia Moment on the drive side of the gearbox	kg m^2
$\Theta_{G,out}[N_G]$	Inertia Moment on the power take-off side of the gearbox	kg m^2

The mass moments of inertia on the drive and the power take-off sides can be defined different for each single gear step. But it is also possible to define the same mass moments of inertia for every single gear step.

$\eta_{G,i}[N_G]$	Number of Teeth Input	–
$\eta_{G,o}[N_G]$	Number of Teeth Output	–

The number of teeth can be defined here. If the user puts in the transmission ratio, AVL CRUISE detects automatically the best fitting number of teeth to get the defined transmission ratio. If it is not possible to get the transmission ratio exactly a suggestion is made for number of teeth which gives the closest possible transmission ratio.

Gear Shift Time

$t_{G,up}[N_G]$	Time Upshifting	s
$t_{G,down}[N_G]$	Time Downshifting	s

If the switch **Gear Shift Time** is activated, the map of the times for upshifting and downshifting dependent on the actual gear number is used. For gears where times are not defined, a default value of 0.1 s is assumed.

Gear Shifting Efficiency for AT Models

$\eta_{G,upshifting}(N_G)$	Efficiency Upshifting (depending on gear)	–
$\eta_{G,downshifting}(N_G)$	Efficiency Downshifting (depending on gear)	–

When the selection button **Gear Shifting Losses** is set to *Efficiency,* the losses during the shifting processes are calculated.

Efficiency and Torque Loss Correction

$\eta_{\mathbf{G,V,3}}(\boldsymbol{N_G})$	Efficiency in the single gear steps	–

The efficiency can be defined separately for the single gear steps. This information is used if the selection button **Losses** is set to *Efficiency* or *Efficiency and Torque Loss.*

$\boldsymbol{M_{G,V,3}}(\dot{\boldsymbol{\varphi}}_{\mathbf{G,in}}, \boldsymbol{N_G})$	Torque Loss in the single gear steps	Nm

The additional torque loss is defined dependent on the gear step and the drive speed of the gearbox. These values are used if the selection button **Losses** is set to *Efficiency and Torque Loss.*

Torque Loss Correction Temperature Dependent

$\boldsymbol{M_{G,V,4}}(\dot{\boldsymbol{\varphi}}_{\mathbf{G,in}}, \boldsymbol{N_{G,T_G}})$	Torque Loss temperature dependent	Nm

This table is used if the switch **Temperature dependent Torque Loss** is activated.

If the selection button **Losses** is set to *Efficiency and Torque Loss* this map replaces the general torque loss definition. If the selection button **Losses** is set to *Torque Loss Map* a correction of the torque loss is made.

Torque Loss Map

$M_{G,V,2}(\dot{\varphi}_{G,in}, M_{G,in}, N_G)$	Torque Loss in the single gear steps	Nm

The torque losses are defined for every single gear step also considering the drive speed and the drive torque of the gearbox.

This map is used if the selection button **Losses** is set to *Torque Loss Map, Torque Loss Map with Torque Division*, or *Torque Loss Map with Torque and Speed Division.*

Torque Loss Map Temperature Dependent

$T_{G,i}$	Temperature i = 1, …, 5	°C

For each activated, temperature dependent torque loss map, the temperature level has to be specified.

$\boldsymbol{M}_{\mathbf{G,V,5,i}}(\dot{\boldsymbol{\varphi}}_{\mathbf{G,in},i}, \boldsymbol{M}_{\mathbf{G,in}}, \boldsymbol{N}_{\mathbf{G}}, i)$	Torque loss map temperature dependent i = 1,…,5	Nm

Here for each activated temperature-dependent torque loss map and for the specified temperature level, the losses are defined depending on speed, input torque and gear. This is only required if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

When the switch **Efficiency Map (for Torque Loss Maps)** is activated, the efficiency for gear losses and temperature-dependent gear losses can be entered in a separate table instead of the torque loss. After pushing the button **Conversion Efficiency in Torque Loss,** the torque loss map is created automatically.

2.4.3 Input and Output Variables

2.4.3.1 Mechanical Connections

$\dot{\boldsymbol{\varphi}}_{\mathbf{G,in}}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{\mathbf{G,in}}$	Angular acceleration on the drive side	rad/s^2
$M_{G,in}$	Torque on the drive side	Nm
$\ddot{\varphi}_{\mathbf{G,out}}$	Angular velocity on the power take-off side	rad/s
$\varphi_{\mathbf{G,out}}$	Angular acceleration on the power take-off side	rad/s^2
$M_{G,out}$	Torque on the power take-off side	Nm

2.4.3.2 Data Input

$N_{G,shift}$	Desired Gear	–
T_G	Temperature	°C
$t_{G,delay}$	Time Delay Gear Dependent	s

2.4.3.3 Data Output

$N_{G,act}$	Current Gear	–
$\dot{\varphi}_{G,out}$	Output Speed	rad/s
$M_{G,out}$	Output Torque	Nm
$\dot{\varphi}_{G,in}$	Input Speed	rad/s
$M_{G,in}$	Input Torque	Nm
$i_{G,act}$	Current Transmission Ratio	–
$P_{G,in}$	Input Power	W
$P_{G,out}$	Output Power	W
$P_{G,loss}$	Power Loss	W

2.4.4 Computation Variables

$i_{G,act}$	Actual gear ratio	–
$M_{G,loss,nom}$	Nominal loss moment	Nm
$M_{G,loss}$	Actual loss moment	Nm
$M_{G,loss,n}$	Rotational speed contribution to the loss moment	Nm
η_G	Actual efficiency of the gearbox	–

2.4.5 Equation System

Actual Gear Ratio
Acquisition of the instantaneous transmission [2]:

$$i_{G,act} = i_G\left[N_{G,act}\right] \tag{2.4.1}$$

Angular Velocity and Acceleration
Computation of the instantaneous angular velocity and the angular acceleration on the power take-off side of the gearbox [2]:

$$\dot{\varphi}_{\text{out}} = \frac{\dot{\varphi}_{\text{in}}}{i_{\text{G,act}}} \tag{2.4.2}$$

$$\ddot{\varphi}_{\text{out}} = \frac{\ddot{\varphi}_{\text{in}}}{i_{\text{G,act}}} \tag{2.4.3}$$

Inertia Moments
The mass moments of inertia are also selected out of the table [2].

$$\Theta_{\text{G,in,act}} = \Theta_{\text{G,in}}\left[N_{\text{G,act}}\right] \tag{2.4.4}$$

$$\Theta_{\text{G,out,act}} = \Theta_{\text{G,out}}\left[N_{\text{G,act}}\right] \tag{2.4.5}$$

Torque Loss
There are four kinds to take the torque loss of the gearbox in consideration.

(1) **Calculation without losses ($Z_{G,i}$ = 1)** [2]

$$M_{\text{G,loss}} = 0 \tag{2.4.6}$$

$$\eta_{\text{G}} = 1 \tag{2.4.7}$$

(2) **Calculation with use of the torque loss map ($Z_{G,i}$ = 2)**
The nominal loss moment is linear interpolated in the loss map [2]:

$$M_{\text{G,loss,nom}} = M_{\text{G,V,2}}\left(\dot{\varphi}_{\text{G,in}}; M_{\text{G,in}}; N_{\text{G,act}}\right) \tag{2.4.8}$$

Is the simulation done with temperature-dependent losses then an additional part is added [2]:

$$M_{\text{G,loss,nom}} = M_{\text{G,V,2}}\left(\dot{\varphi}_{\text{G,in}}; M_{\text{G,in}}; N_{\text{G,act}}\right) + M_{\text{G,V,4}}\left(\dot{\varphi}_{\text{G,in}}, N_{\text{G}}, T_{\text{G}}\right) \tag{2.4.9}$$

The efficiency is now calculated as follows [2]:

$$\eta_G = 1 - \frac{M_{\text{G,loss,nom}}}{M_{\text{G,in}}} \tag{2.4.10}$$

(3) **Calculation with use of the efficiency value and the torque loss ($Z_{G,i}$ = 3)**
The rotational speed contribution to the torque loss is linear interpolated in the loss curve [2]:

$$M_{G,loss,n} = M_{G,V,3}\left(\dot{\varphi}_{G,in}; N_{G,act}\right) \tag{2.4.11}$$

Is the simulation done with temperature-dependent losses then the torque loss is interpolated out of the map $M_{G,V,4}$ $(\dot{\varphi}_{G,in}, N_G, T_G)$ [2]:

$$M_{G,loss,n} = M_{G,V,4}\left(\dot{\varphi}_{G,in}; N_{G,act}; T_G\right) \tag{2.4.12}$$

Also the efficiency value is selected for the actual gear [2]:

$$\eta_G = \eta_{G,V,3}(N_{G,act}) \tag{2.4.13}$$

The actual torque loss is evaluated as followed [2]:

$$M_{G,loss} = M_{G,in} \cdot (1 - \eta_G) + M_{G,loss,n} \tag{2.4.14}$$

(4) **Calculation with use of the efficiency value ($Z_{G,i}$ = 4)**
The efficiency value is selected for the actual gear [2]:

$$\eta_G = \eta_{G,V,3}(N_{G,act}) \tag{2.4.15}$$

The actual torque loss is evaluated as followed [2]:

$$M_{G,loss} = M_{G,in} \cdot (1 - \eta_G) \tag{2.4.16}$$

2.5 CVT—Continuously Variable Transmission (H)

By means of this component, an infinitely variable CVT gearbox can be simulated. The Continuously Variable Transmission can convert every point on the engine's operating curve to an operating curve of its own, and every engine operating curve into an operating range within the field of potential driving conditions. Its advantage over conventional fixed-ratio transmissions lies in the potential for enhancing performance and fuel economy while reducing exhaust emissions. However, full exploitation of this theoretical capability would entail overdrive factors that are not realizable up to now [1].

With the model of the CVT gearbox included in AVL CRUISE it is possible to change the transmission between two user-defined threshold values. The adjusting speed between different transmissions is internal fixed at a constant value.

The change in transmission is done in form of a kinematic coupling. The advantage of this is that there is no additional degree of freedom. Thereby the

calculation time is decreasing. The disadvantage is that the transitions might be not real harmonic and that there is the need to change the equation system for every change in transmission [1].

Because there is no possibility to define an unlimited transmission there is a clutch needed for starting. This clutch will be controlled by the control module CVT control which is also controlling the CVT gearbox [1].

2.5.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Power Transmission
without slip
with slip
The calculation of the CVT does not include chain slip. A purely kinematic coupling is performed.

Selection Button Power Transmission
without slip
with slip
The calculation of the CVT includes also chain slip. A dynamic coupling between input and output is made.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent
At this selection no losses are considered in the CVT when calculating without slip.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent
At this selection only the efficiency map is considered when calculating without slip.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection the efficiency map and the torque loss map is considered when calculating without slip.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection the efficiency map and the temperature dependent torque loss map is considered when calculating without slip.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection only the torque loss map is considered when calculating without slip.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection data from the torque loss map is used, corrected by input data from the temperature-dependent torque loss map.

Selection Button Losses at "Without Slip"
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Efficiency and Torque Loss Correction Temperature Dependent
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

In this case, the losses are calculated with up to 5 'Torque Loss Maps Temperature Dependent' where each map is associated with a user-defined constant temperature value. An interpolation between these maps is done so that for every time step a torque loss can be generated. The temperature used in the calculation comes through the Data Bus input *Temperature.* For example, it could be connected with one of the 5 cycle-dependent temperature characteristics in the component *Vehicle.*

Selection Button Losses at "With Slip"
Deactivated
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection no losses are considered when calculating with slip.

Selection Button Losses at "With Slip"
Deactivated
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection the torque loss map is considered when calculating with slip.

Selection Button Losses at "With Slip"
Deactivated
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

At this selection the torque loss map and the temperature-dependent torque loss is considered when calculating with slip. Both losses are added.

Selection Button Losses at "With Slip"
Deactivated
Torque Loss Map
Torque Loss Map and Torque Loss Correction Temperature Dependent
Torque Loss Map Temperature Dependent

In this case, the losses are calculated with up to 5 'Torque Loss Maps Temperature Dependent' where each map is associated with a user-defined constant temperature value. An interpolation between these maps is done so that for every time step a torque loss can be generated. The temperature used in the calculation comes

through the Data Bus input *Temperature.* For example, it could be connected with one of the 5 cycle-dependent temperature characteristics in the component *Vehicle.*

Switch Efficiency Map (for Torque Loss Maps)
When this switch is activated, the efficiency can be entered in a separate table instead of the torque loss.

After pushing the button *Conversion Efficiency in Torque Loss,* the torque loss map is created automatically.

Switches Torque Loss Map 1, …, 5
With these switches, the associated loss maps can be activated for up to 5 temperature levels. This selection is only available if the selection button **Losses** is set to *Torque Loss Map Temperature Dependent.*

Selection Button Adjustment Time
Fixed Value
Speed Dependent
Speed Dependent from Data Bus
The adjustment time is the time the CVT needs to adjust from minimum to maximum transmission or vice versa. At this selection the adjustment time is a fixed value.

Selection Button Adjustment Time
Fixed Value
Speed Dependent
Speed Dependent from Data Bus
The adjustment time depends on the input speed of the CVT.

Selection Button Adjustment Time
Fixed Value
Speed Dependent
Speed Dependent from Data Bus
The adjustment time depends on the speed connectivity from the Data Bus.

2.5.2 User-Defined Variables

T_H	Adjustment Time	s

The adjustment time is the time the CVT needs to adjust from minimum to maximum transmission or vice versa.

$i_{H,lim}$	Switching Threshold	–

The switching threshold is the minimum difference in transmission ratio which is needed to change the transmission ratio. This input is only needed when the CVT is calculated without slip.

$i_{H,min}$	Minimum Ratio	–
$i_{H,max}$	Maximum Ratio	–

Here the minimum and the maximum transmission have to be defined. Between these two threshold values the transmission can change infinitely, i.e., the transmission can reach every possible value between the two thresholds.

$\theta_{H,in}$	Inertia Moment on the drive side	kg m^2
$\theta_{H,out}$	Inertia Moment on the power take-off side	kg m^2

The mass moments of inertia have to be defined separately for the drive and the power take-off side (Fig. 2.6).

Slip Description
Is active when the CVT is calculated with slip.

$M_{H,nom}$	Nominal Torque	Nm
$s_{H,nom}$	Nominal Slip	%
$i_{H,nom}$	Nominal Transmission Ratio	–
$s_{H,diff}$	Slip Change	%
$\kappa_H(M_H/M_{H,nom})$	Relative Slip Characteristic ($=s_H/s_{H,nom}$)	–

The Slip Characteristic describes the slip behavior of the CVT as relative map which depends on its nominal values.

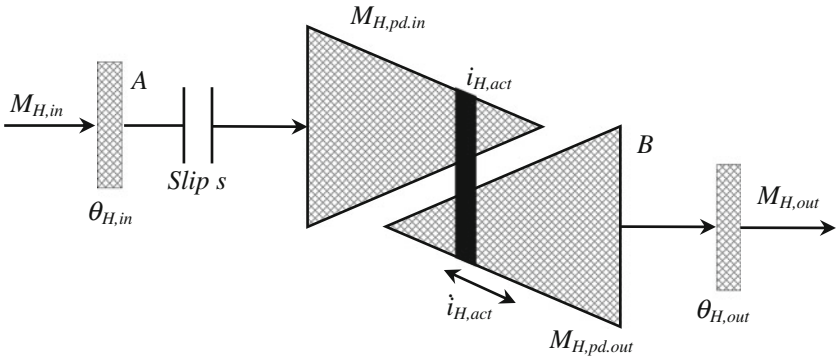


Fig. 2.6 Principle representation of a CVT gearbox [2]

Efficiency and Torque Loss Correction

$\eta_{H,V,2}(i_H)$	Efficiency	–

The efficiency can be defined as function of the transmission ratio.

$M_{H,V,2}(\dot{\varphi}_{H,in}, i_H)$	Torque loss	Nm

The additional torque loss is defined as function of the transmission ratio and the drive speed.

These data can only be used for a calculation of a CVT without slip.

Torque Loss Correction Temperature Dependent

$M_{H,V,3}(\dot{\varphi}_{H,in}, i_H, T_H)$	Torque loss temperature dependent	Nm

Here an additional temperature-dependent torque loss can be defined.

Torque Loss Map

$\boldsymbol{M_{H,V,1}(\dot{\varphi}_{H,in}, M_{H,in}, i_H)}$	Torque Loss related to the drive side	Nm

The torque lost in the transmission is defined in a table depending on the drive speed, the drive torque and the actual transmission ratio. These data can only be used for a calculation of a CVT with slip.

Torque Loss Map Temperature Dependent

$T_{H,i}$	Temperature i = 1, …, 5	°C

For each activated temperature-dependent torque loss map, the temperature level has to be specified.

$\boldsymbol{M_{H,V,5,1}(\dot{\varphi}_{H,in,i}, M_{H,in,i}, N_{H,i})}$	Torque loss map temperature dependent i = 1, …, 5	Nm

Here for each activated temperature-dependent torque loss map and for the specified temperature level, the losses are defined depending on speed, input torque and gear. This is only required if the selection button **Losses** is set to *Torque Loss Map Temperature Dependent.*

When the switch **Efficiency Map (for Torque Loss Maps)** is activated, the efficiency for gear losses and temperature-dependent gear losses can be entered in a separate table instead of the torque loss. After pushing the button **Conversion Efficiency in Torque Loss,** the torque loss map is created automatically.

Adjustment Time Speed Dependent

T_H	Adjustment Time	s
$T_H\dot{\varphi}$	Adjustment time Speed Dependent	s

The adjustment time is the time the CVT needs to adjust from minimum to maximum transmission or vice versa.

2.5.3 Input and Output Variables

2.5.3.1 Mechanical Connections

$M_{H,in}$	Input torque	Nm
$M_{H,out}$	Output torque	Nm
$\dot{\varphi}_{H,in}$	Input speed	rad/s
$\ddot{\varphi}_{H,in}$	Angular acceleration on the drive side	rad/s^2
$\dot{\varphi}_{H,out}$	Output speed	rad/s
$\ddot{\varphi}_{H,out}$	Angular acceleration on the power take-off side	rad/s^2

2.5.3.2 Data Input

$i_{H,rated}$	Desired Transmission Ratio	–
T_H	Temperature	°C
$\dot{\varphi}_{H,ext}$	Speed External	rad/s

2.5.3.3 Data Output

$i_{H,act}$	Current Transmission Ratio	–
$N_{H,act}$	Current Gear	–
$\dot{\varphi}_{H,in}$	Input Speed	rad/s
$M_{H,in}$	Input Torque	Nm
$\dot{\varphi}_{H,out}$	Output Speed	rad/s
$M_{H,out}$	Output Torque	Nm
$P_{H,in}$	Input Power	W
$P_{H,out}$	Output Power	W
$P_{H,loss}$	Power Loss	W

2.5.4 Computation Variables

$\Delta i_{\mathrm{H,act}}$	Transmission gap in gear ratio	–
$M_{\mathrm{H,loss}}$	Instantaneous total moment of loss in the gearbox	Nm

2.5.5 Equation System

Deviation in Gear Ratio

For the gear selection the difference between target and actual transmission is taken [2]:

$$\Delta i_{\mathrm{H,act}} = i_{\mathrm{H,requ}} - i_{\mathrm{H,act}} \tag{2.5.1}$$

If this gear shifting step is great enough and the gear ratio limits are not reached the gear shifting process will be done.

(a) **Calculation without slip**
The calculation without slip is done with kinematic equations only. The input and output speed relation is fixed. Also the input and output torque are defined by the transmission ratio.

(b) **Calculation with slip**
In this case also the force equations are used (dynamic simulation):
For the actual ratio the reference slip is calculated with the following formula out of the Slip Characteristic [2]:

$$s_{\mathrm{H,act}} = \frac{s_{\mathrm{H,diff}}}{s_{\mathrm{H,ref}}} \tag{2.5.2}$$

$$s_{\mathrm{H,ref}} = s_{\mathrm{H,nom}} \cdot \left(s_{\mathrm{H,diff}} \cdot \left(i_{\mathrm{H,act}} - i_{\mathrm{H,nom}}\right) + 1\right) \tag{2.5.3}$$

Using the relation between actual and nominal CVT-torque the slip relation can be evaluated.
Now the actual slip is determined for the reference slip and the slip relation [2].

$$\dot{\varphi}_{\mathrm{ref}} = \sqrt{\dot{\varphi}_{\mathrm{break}}^2 + \left(|\dot{\varphi}_{\mathrm{Belt}}| + |\Delta_{\dot{\varphi}}|\right)^2}$$

with $\dot{\varphi}_{\mathrm{break}} = 0.1$

$$\begin{aligned} \Delta_{\dot{\varphi}} &= \dot{\varphi}_{\mathrm{H,in}} - \dot{\varphi}_{\mathrm{Belt}} \\ \dot{\varphi}_{\mathrm{Belt}} &= \dot{\varphi}_{\mathrm{H,out}} \cdot i_{\mathrm{H,act}} \\ s_{\mathrm{H}} &= \frac{\Delta_{\dot{\varphi}}}{\dot{\varphi}_{\mathrm{ref}}} \end{aligned} \tag{2.5.4}$$

Torque Loss

There are three kinds to take the torque loss of the gearbox in consideration.

(1) **Calculation without losses ($Z_{H,i}$ = 1)** [2]

$$M_{H,loss} = 0 \tag{2.5.5}$$

$$\eta_H = 1 \tag{2.5.6}$$

(2) **Calculation with use of the torque loss map ($Z_{H,i}$ = 2)**
The nominal loss moment (Fig. 2.7) is linear interpolated in the loss map [2].

$$M_{H,loss,nom} = M_{H,V,2}\left(\dot{\varphi}_{H,in}; M_{H,in}; i_{H,act}\right) \tag{2.5.7}$$

If the simulation is done with temperature-dependent losses then an additional part is added [2]:

$$M_{H,loss,nom} = M_{H,V,2}\left(\dot{\varphi}_{H,in}; M_{H,in}; i_{H,act}\right) + M_{H,V,4}\left(\dot{\varphi}_{H,in}; i_H; T_H\right) \tag{2.5.8}$$

$$\eta_H = 1 - \frac{M_{H,loss,nom}}{M_{H,in}} \tag{2.5.9}$$

The actual torque loss is determined by the following formula [2].

$$M_{H,loss} = M_{H,in} \cdot (1 - \eta_H) - M_{H,loss,nom} \tag{2.5.10}$$

(3) **Calculation with use of the efficiency value and the torque loss ($Z_{G,i}$ = 3)**
The nominal loss is linear interpolated in the loss curve [2]:

$$M_{H,loss,nom} = M_{H,V,3}\left(\dot{\varphi}_{H,in}; i_{H,act}\right) \tag{2.5.11}$$

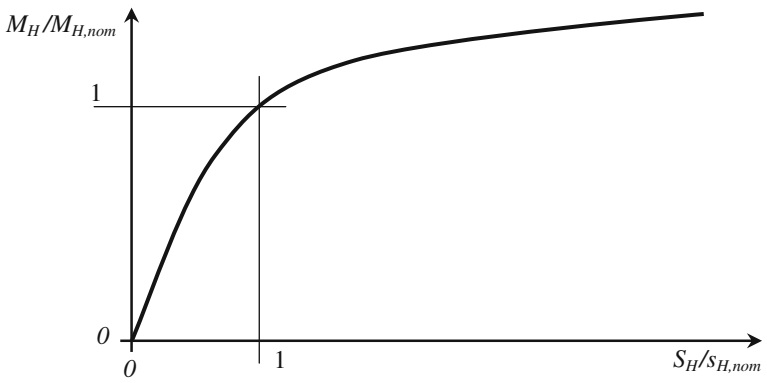


Fig. 2.7 Nominal loss moment variation [2]

Is the simulation done with temperature-dependent losses then the torque loss is interpolated out of the map $M_{H,V,4}\left(\dot{\varphi}_{H,in}, N_H, T_H\right)$ [2]:

$$M_{H,loss,nom} = M_{H,V,4}\left(\dot{\varphi}_{H,in}; i_{H,act}; T_H\right) \tag{2.5.12}$$

Also the efficiency value is selected for the actual gear [2]:

$$\eta_H = \eta_{H,V,3}\left(i_{H,act}\right) \tag{2.5.13}$$

The actual torque loss is evaluated as followed [2]:

$$M_{H,loss} = M_{H,in} \cdot (1 - \eta_H) - M_{H,loss,nom} \tag{2.5.14}$$

4) **Calculation with use of the Torque Loss Map Temperature dependent ($Z_{G,i} = 4$)**
The nominal loss is linear interpolated in the loss curve [2]:

$$M_{H,loss,nom} = M_{H,V,5}\left(T_H; i_{H,act}; \dot{\varphi}_{H,in}; N_H\right) \tag{2.5.15}$$

2.6 Single Ratio Transmission (D)

The Single Ratio Transmission is a gear step with fixed ratio. It can be used, e.g., as transmission step of the differential (final drive unit).

A drive torque will be transferred to a power take-off torque of the transmission step by considering the transmission, the mass moments of inertia and the moment of loss [1].

2.6.1 Properties

Switch Variation
With this switch the single ratio transmission can be given free for variation. For the single ratio transmission the transmission ratio can be changed by multiplication with an additional factor. The setup of the variation parameters is done in the folder.

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Definition
Transmission Ratio
Number of Teeth
The transmission ratio can be defined in this case.

Selection Button Definition
Transmission Ratio
Number of Teeth
In this case the transmission ratio is defined by the number of teeth of input and output.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map Temperature Dependent
In this case no losses are calculated in the single ratio transmission.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map Temperature Dependent
In this case, the losses are calculated by a constant efficiency value.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map Temperature Dependent
In this case, the losses are calculated by a constant efficiency value and by a curve which depends on the drive speed.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map

Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map Temperature Dependent

In this case the losses are interpolated out of a torque loss map, which depends on the gear position, the drive speed and the drive torque. At the torque and speed division a special approximation of the maps is made by cutting through the map at the defined torque and speed values.

Selection Button Losses
Deactivated
Efficiency
Efficiency and Torque Loss Correction
Torque Loss Map
Torque Loss Map with Torque Division
Torque Loss Map with Torque and Speed Division
Torque Loss Map Temperature Dependent

In this case, the losses are calculated with the usage of up to 5 torque loss maps *Torque Loss temperature dependent* where each map is associated with a user-defined constant temperature value. An interpolation between these maps is done so that for every time step a torque loss can be generated. The temperature used in the calculation comes through the Data Bus input *Temperature.* For example, it could be connected with one of the 5 cycle-dependent temperature characteristics in the component *Vehicle.*

Switch Torque Loss Correction Temperature Dependent
Here a temperature-dependent torque loss map *Torque Loss Correction temperature dependent* can be activated.

Switch Efficiency Map (for Torque Loss Maps)
When this switch is activated, the efficiency can be entered in a separate table instead of the torque loss.

Switches Torque Loss Map 1–5
With these switches, for up to 5 temperature levels the associated loss maps can be activated. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition
Deactivated
Torque Partition
Torque and Speed Partition

In this case no partition of torque or speed is done. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition
Deactivated
Torque Partition
Torque and Speed Partition

In this case a torque partition is done. A special approximation of the maps is made by cutting through the map at the defined torque values. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Selection Button Torque Loss Partition

Deactivated

Torque Partition

Torque and Speed Partition

In this case a torque and speed partition is done. A special approximation of the maps is made by cutting through the map at the defined torque and speed values. This selection is only available if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

Table Division Values for the Torque Loss

For the torque and the speed range the borders for activation and deactivation can be defined here. The values are defined in percentage of the maximum speed and torque values.

2.6.2 User-Defined Variables

i_D	Transmission Ratio	–

The overall ratio can be defined if this case of input is chosen in the properties.

$Z_{D,1}$	Number of Teeth Input	–
$Z_{D,2}$	Number of Teeth Output	–

The user can put in the transmission ratio or the number of teeth depending on the selection in the properties (Fig. 2.8).

$\theta_{D,in}$	Inertia Moment, drive side	kg m^2
$\theta_{D,out}$	Inertia Moment, power take-off side	kg m^2

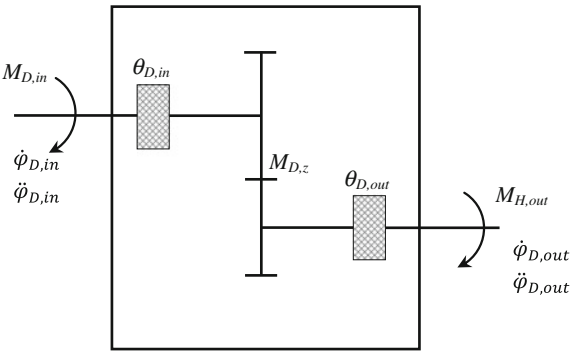


Fig. 2.8 Principle representation of a Single Ratio Transmission [2]

Efficiency and Torque Loss Correction

$\eta_{D,V,3}$	Efficiency	–

The efficiency in the single ratio transmission is a fixed value.

$M_{D,V,3}(\dot{\varphi}_{D,in})$	Torque Loss on the drive side	Nm

The additional torque loss is defined dependent on the drive speed.

Torque Loss Correction Temperature Dependent

$M_{D,V,4}(\dot{\varphi}_{D,in}, T_D)$	Torque Loss temperature dependent	Nm

Here an additional temperature-dependent torque loss can be defined. This table is used if the switch **Torque Loss Correction temperature dependent** is activated.

If the selection button **Losses** is set to *Efficiency & Torque Loss* this map replaces the general torque loss definition.

If the selection button **Losses** is set to *Torque Loss Map* a correction of the torque loss is made.

Torque Loss Map

$M_{D,V,2}(\dot{\varphi}_{D,in}, M_{D,in})$	Torque Loss on the drive side	Nm

Torque Loss on the drive side. The torque loss is defined considering the drive speed and the drive torque of the single ratio transmission.

Torque Loss Map Temperature Dependent

$T_{D,i}$	Temperature i = 1, …, 5	°C

For each activated, temperature-dependent torque loss map, the temperature level has to be specified.

$M_{D,V,5,i}(\dot{\varphi}_{D,in,i}, M_{D,in,i})$	Torque loss map temperature dependent i = 1, …, 5	Nm

Here for each activated, temperature dependent torque loss map and for the specified temperature level, the losses are defined depending on speed and input torque. This is only required if the selection button **Losses** is set to *Torque Loss Map temperature dependent.*

When the switch **Efficiency Map (for Torque Loss Maps)** is activated, the efficiency can be entered in a separate table instead of the torque loss.

2.6.3 Input and Output Variables

2.6.3.1 Mechanical Connections

$\dot{\varphi}_{D,in}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{D,in}$	Angular acceleration on the drive side	rad/s^2
$M_{D,in}$	Torque on the drive side	Nm
$\dot{\varphi}_{D,out}$	Angular velocity on the power take-off side	rad/s
$\ddot{\varphi}_{D,out}$	Angular acceleration on the power take-off side	rad/s^2
$M_{D,out}$	Torque on the power take-off side	Nm

2.6.3.2 Data Input

T_D	Temperature	°C

2.6.3.3 Data Output

$\dot{\varphi}_{D,out}$	Output Speed	rad/s
$M_{D,out}$	Output Torque	Nm
$\dot{\varphi}_{D,in}$	Input Speed	rad/s
$M_{D,in}$	Input Torque	Nm
$P_{D,in}$	Input Power	W
$P_{D,out}$	Output Power	W
$P_{D,loss}$	Power Loss	W

2.6.4 Computation Variables

$M_{D,loss}$	Loss moment	Nm
$M_{D,loss,nom}$	Nominal loss moment	Nm
$M_{D,loss,n}$	Rotational speed contribution to the loss moment	Nm
$N_{D,act}$	Actual gear position	–
η_D	Actual efficiency of the transmission box	–

2.6.5 Equation System

2.6.5.1 Transmission ratio

If the numbers of teeth are defined for the single transmission step, then the gear ratio can be calculated: $i_D = \frac{Z_{D,2}}{Z_{D,1}}$.

Angular Velocity and Acceleration [2]

$$\dot{\varphi}_{D,out} = \frac{\dot{\varphi}_{D,in}}{i_D} \tag{2.6.1}$$

$$\ddot{\varphi}_{D,out} = \frac{\ddot{\varphi}_{D,in}}{i_D} \tag{2.6.2}$$

2.6.5.2 Torque Loss

There are four kinds to take the torque loss of the gearbox in consideration.

(1) **Calculation without losses ($Z_{D,i}$ = 1)** [2]

$$M_{D,loss} = 0 \tag{2.6.3}$$

$$\eta_D = 1 \tag{2.6.4}$$

(2) **Calculation with use of the torque loss map ($Z_{D,i}$ = 2)**
The nominal loss moment is linear interpolated in the loss map [2].

$$M_{D,loss,nom} = M_{D,V,2}\left(\dot{\varphi}_{D,in}; M_{D,in}\right) \tag{2.6.5}$$

Is the simulation done with temperature-dependent losses then an additional part is added [2]:

$$M_{D,loss,nom} = M_{D,V,2}\left(\dot{\varphi}_{D,in}; M_{D,in}\right) + M_{D,V,4}\left(\dot{\varphi}_{D,in}; T_D\right) \tag{2.6.6}$$

The efficiency is calculated as follows [2]:

$$\eta_D = 1 - \frac{M_{D,loss,nom}}{M_{D,in}} \tag{2.6.7}$$

(3) **Calculation with use of the efficiency value and the torque loss ($Z_{D,i} = 3$)**
The rotational speed contribution to the torque loss is linear interpolated in the loss curve [2]:

$$M_{D,loss,nom} = M_{D,V,3}\left(\dot{\varphi}_{D,in}\right) \tag{2.6.8}$$

Is the simulation done with temperature-dependent losses then the torque loss is interpolated out of the map $M_{D,V,4}\left(\dot{\varphi}_{D,in}; T_D\right)$ [2]:

$$M_{D,loss,nom} = M_{D,V,4}\left(\dot{\varphi}_{D,in}; T_D\right) \tag{2.6.9}$$

The actual torque loss is evaluated as followed [2]:

$$M_{D,loss} = M_{D,in} \cdot \left(1 - \eta_{D,V,3}\right) + M_{D,loss,nom} \tag{2.6.10}$$

(4) **Calculation with use of the efficiency value *($Z_{D,i} = 4$)***
The actual torque loss is evaluated as followed [2]:

$$M_{D,loss} = M_{D,in} \cdot \left(1 - \eta_{D,V,3}\right) \tag{2.6.11}$$

2.7 Differential (N)

The differential unit compensates for discrepancies in the respective rotation rates of the drive wheels: between inside and outside wheels during cornering and between different drive axles on 4WD vehicles [1].

With rare exceptions for special applications, the differential is a bevel gear drive unit. When the output bevel gears on the left and right sides (most common arrangement) are of equal dimensions, the differential gears act as a balance arm to equalize the distribution of torque to the left and right wheels [1].

When unilateral variations in road surfaces result in different coefficients of friction at the respective wheels, this balance effect limits the effective drive torque to a level defined as twice the traction force available at the wheel (tire) with the lower coefficient of friction. This wheel then responds to the application of excessive force by spinning. To avoid such effects a positive lock is available at the component [1].

In the differential it is possible to define a torque split factor (Fig. 2.9).

This is required if it is used as a central differential for a four-wheel drive, as sometimes you want to have either more torque transferred to the front or the rear axle. This is used for preserving the driving quality of the corresponding two wheel driven car which is either front wheel driven or rear wheel driven [1].

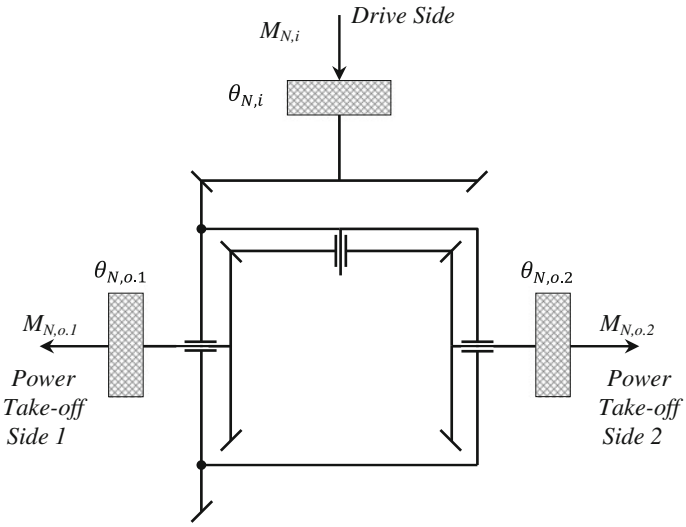


Fig. 2.9 Principle representation of a Differential [2]

2.7.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Losses
Deactivated
Efficiency
In this case, the calculation of losses is deactivated.

Selection Button Losses
Deactivated
Efficiency
In this case, the losses are calculated through a user-defined input of a constant 'Stationary Efficiency' value.

2.7.2 User-Defined Variables

$Z_{N,lock}$	Control parameter for locked/unlocked/Split Factor from Data Bus	–

This button allows the user to run the differential in a locked or an unlocked mode or to get the torque split factor from Data Bus.

Unlocked mode means that the two power take-off torques are the same and the speeds can be different. In the locked mode there is a rigid connection between the

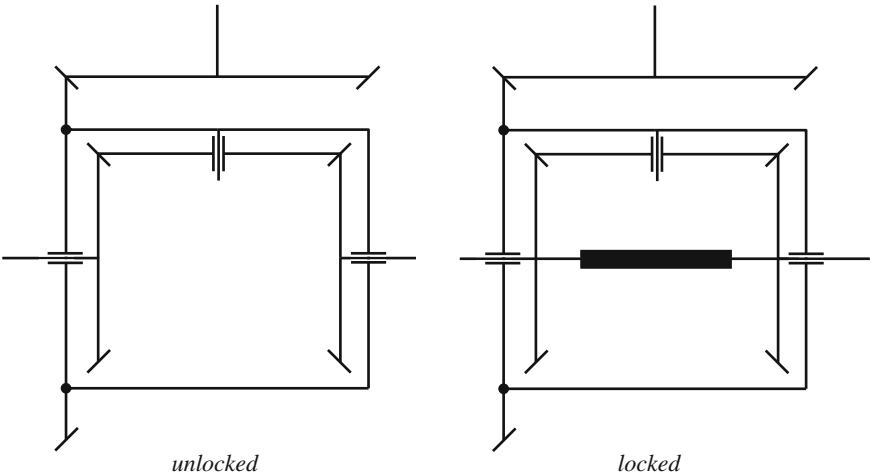


Fig. 2.10 Lock modes of Differential [2]

two power take-off sides. That means that the speeds are the same and the torques can be different (Fig. 2.10).

i_N	Torque slip factor $M_{o,2}/M_{o,1}$	–

To have a different torque output on the power take-off side, choose the corresponding splitting ratio. To have the same torques on both outgoing sides, the splitting ratio equals 1.

$\theta_{N,i}$	Inertia Moment on the drive side	kg m^2
$\theta_{N,o,1(2)}$	Inertia Moment on the power take-off side	kg m^2

Stationary Efficiency

$\eta_{N,stat}$	Efficiency	–

The stationary efficiency η is the efficiency of the differential with fixed input shaft.

If the properties switch 'Losses' is set to 'Efficiency', AVL CRUISE calculates in every time step the actual losses depending on the fixed efficiency η.

2.7.3 Input and Output Variables

2.7.3.1 Mechanical Connections

$\dot{\boldsymbol{\varphi}}_{\mathbf{N,in}}$	Angular velocity on the drive side	rad/s
$\varphi_{\mathbf{N,in}}$	Angular acceleration on the drive side	rad/s^2
$M_{\mathrm{N,in}}$	Torque on the drive side	Nm
$\dot{\boldsymbol{\varphi}}_{\mathbf{N,out,1(2)}}$	Angular velocity on the power take-off side 1(2)	rad/s
$\varphi_{\mathbf{N,out,1(2)}}$	Angular acceleration on the power take-off side 1(2)	rad/s^2
$M_{\mathrm{N,out,1(2)}}$	Torque on the power take-off side 1(2)	Nm

2.7.3.2 Data Input

$i_{\mathrm{N,ext}}$	Torque Split Factor External	–

2.7.3.3 Data Output

$\dot{\varphi}_{\mathrm{N,in}}$	Input Speed	rad/s
$M_{\mathrm{N,in}}$	Input Torque	Nm
$M_{\mathrm{N,lock}}$	Lock Torque	Nm
$\dot{\varphi}_{\mathrm{N,out,1(2)}}$	Output Speed 1(2)	rad/s
$M_{\mathrm{N,out,1(2)}}$	Output Torque 1(2)	Nm
$P_{\mathrm{N,in}}$	Input Power	W
$P_{\mathrm{N,out,1(2)}}$	Output Power 1 (2)	W
$P_{\mathrm{N,loss}}$	Power Loss	W

2.7.4 Computation Variables

$M_{\mathrm{N,lock}}$	Lock Moment	Nm
$i_{\mathrm{N,sum}}$	Summation Moment ratio	–
$i_{\mathrm{N,inv}}$	Split ratio inversion	–

2.7.5 Equation System

Gear Ratio

At first the split ratio for the inversion is determined [2]:

$$i_{\mathrm{N,inv}} = \frac{1}{i_{\mathrm{N}}} \tag{2.7.1}$$

The second ratio which is calculated is the ratio for the summation [2]:

$$i_{\mathrm{N,sum}} = 1 + i_{\mathrm{N}} \tag{2.7.2}$$

Split Equations

Unlocked differential

For the unlocked differential the following equation for the torque is used [2]:

$$\dot{\varphi}_{\mathrm{N,in}} \cdot (i_n + 1) = \dot{\varphi}_{\mathrm{N,out,1}} + \dot{\varphi}_{\mathrm{N,out,2}} \cdot i_{\mathrm{N}} \tag{2.7.3}$$

and for the lock moment [2]:

$$\mathrm{M}_{\mathrm{N,lock}} = 0 \tag{2.7.4}$$

Locked differential

For the locked differential both takeoffs have the same speed [2]:

$$\dot{\varphi}_{\mathrm{N,out,1}} = \dot{\varphi}_{\mathrm{N,out,2}} \tag{2.7.5}$$

The lock moment is defined as [2]:

$$M_{\mathrm{N,lock}} = M_{\mathrm{N,out,1}} - M_{\mathrm{N,out,2}} \tag{2.7.6}$$

2.8 Planetary Gearbox (PG)

The Planetary Gearbox belongs to the power split devices. It consists of three main components: the sun gear, the planet carrier (with planets), and the ring gear. This gearbox can be used in hybrid systems, where vehicles be driven using different power suppliers. With the help of a planetary gear it is possible to add torque and speed with different directions at the transmission input shafts [1].

In a planetary gear system, the speed ratio and the direction of rotation can be changed according to which member is fixed. There are three types of planetary gear mechanisms, depending upon which member is locked (locked **ring gear**, or locked **planet carrier**, or locked **sun gear**) [1].

2.8.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Input Mode
Base Ratio
Number of Teeth
In this case, the gear ratio between ring gear and sun gear, the so-called base ratio of a planetary gearbox, are required.

Selection Button Input Mode
Base Ratio
Number of Teeth
In this case, the number of sun gear's teeth and the number of ring gear's teeth are required.

Selection Button Losses
Deactivated
Efficiency
In this case, the calculation of losses is deactivated.

Selection Button Losses
Deactivated
Efficiency
In this case, the losses are calculated through a user-defined input of a constant 'Stationary Efficiency' value.

2.8.2 User-Defined Variables

$Z_{PG,lock}$	Control parameter for locked or unlocked	–

This button allows the user to run the planetary gearbox in a locked or an unlocked mode.

Unlocked mode means that on the three shafts (planet carrier, sun, and ring) torques can be different and the speeds can also be different. In the locked mode there is a rigid connection between two of them.

That means that the speeds on all shafts are the same (because of the speed's equation at the planetary gear) and the torques can be different.

$i_{PG,o}$	Base Ratio	–

Base ratio is quotient of ring gear's teeth to the sun gear's teeth.

$\theta_{PG,C}$	Inertia Moment Planet Carrier	kg m^2
$\theta_{PG,S}$	Inertia Moment Sun Gear	kg m^2
$\theta_{PG,R}$	Inertia Moment Ring Gear	kg m^2
$N_{PG,S}$	Number of teeth Sun Gear	–
$Z_{PG,R}$	Number of teeth Ring Gear	–

The number of teeth for the ring gear is negative because of its internal toothing.

Stationary Efficiency

$\eta_{PG,stat}$	Efficiency	–

The Stationary Efficiency $\boldsymbol{\eta}$ is the efficiency of the so-called 'Base Gearbox' which is the planetary gearbox with fixed planet carrier. In this case the planetary gearbox works like a single transmission.

If the properties switch 'Losses' is set to 'Efficiency' AVL CRUISE calculates in every time step the actual losses depending on the fixed efficiency η and the actual power flow direction.

2.8.3 Input and Output Variables

2.8.3.1 Mechanical Connections

$\dot{\varphi}_{PG,C}$	Angular velocity of the Planet Carrier	rad/s
$\ddot{\varphi}_{PG,C}$	Angular acceleration of the Planet Carrier	rad/s^2
$M_{PG,C}$	Torque on the Planet Carrier	Nm
$\dot{\varphi}_{PG,S}$	Angular velocity of the Sun Gear	rad/s
$\ddot{\varphi}_{PG,S}$	Angular acceleration of the Sun Gear	rad/s^2
$M_{PG,S}$	Torque on the Sun Gear	Nm
$\dot{\varphi}_{PG,R}$	Angular velocity of the Ring Gear	rad/s
$\ddot{\varphi}_{PG,R}$	Angular acceleration of the Ring Gear	rad/s^2
$M_{PG,R}$	Torque on the Ring Gear	Nm

2.8.3.2 Data Output

$\dot{\varphi}_{PG,C}$	Angular velocity of the Planet Carrier	rad/s
$\dot{\varphi}_{PG,S}$	Angular velocity of the Sun Gear	rad/s

(continued)

$\dot{\varphi}_{PG,R}$	Angular velocity of the Ring Gear	rad/s
$M_{PG,C}$	Torque on the Planet Carrier	Nm
$M_{PG,S}$	Torque on the Sun Gear	Nm
$M_{PG,R}$	Torque on the Ring Gear	Nm
$P_{PG,C}$	Power—Planet Carrier	W
$P_{PG,S}$	Power—Sun Gear	W
$P_{PG,R}$	Power—Ring Gear	W
$P_{PG,loss}$	Power Loss	W

2.8.4 Equation System

The speed equation of the planetary gearbox [2]:

$$\dot{\varphi}_{PG,S} - \left(1 + i_{PG,o}\right) \cdot \dot{\varphi}_{PG,C} + i_{PG,o} \cdot \dot{\varphi}_{PG,R} = 0 \tag{2.8.1}$$

Locked Planetary Gearbox
For the locked planetary gearbox all shafts have the same speed [2]:

$$\dot{\varphi}_{PG,S} = \dot{\varphi}_{PG,C} = \dot{\varphi}_{PG,R} \tag{2.8.2}$$

Under the balance conditions, the summation of all torques acting on planetary gear is equal to zero by the stationary state of motion [2]:

$$M_{PG,S} + M_{PG,C} + M_{PG,R} = 0 \tag{2.8.3}$$

Two of the three torques always possess the same sign. The summation of their absolute values is equal to the third torque. The shaft, which this summation leads to, is defined as summation shaft. The others are difference shafts.

There are two characteristic rules, which are very useful to analyze the complex interaction on double pinion gearbox:

The summation shaft's torque and difference shafts torques has opposite signs.

The torques of both Difference Shafts have the same sign.

2.9 Internal Combustion Engine (E)

The component engine contains a model for an internal combustion engine. As the characteristic curves for the full load, the fuel consumption and others can be freely defined by the user. It is possible to define a gasoline engine as well as a diesel engine [1].

In this component a temperature model is included to consider the influence of the temperature on the fuel consumption and emissions while the engine is cold.

The engine will be modeled by a structure of characteristic curves and maps [1].

2.9.1 Properties

Switch Variation

With this switch the internal combustion engine can be given free for variation. For the internal combustion engine the engine displacement can be varied. The setup of the variation parameters is done in the folder.

Switch Output

A result output for this component is made if this switch is activated.

Switch Use for Reference

This switch is used to select one reference engine if more engines are used within a model. Out from this engine the following data are calculated, which can then be used in the Calculation Tasks:

- Minimum speed
- Maximum speed
- Maximum torque
- Speed at maximum torque
- Maximum power
- Speed at maximum power

Selection Button Intended for Calculation of

Performance
Performance and Consumption
Performance, Consumption, and Emission
Performance, Consumption, and CO_2 Emission
Performance, Consumption, Emission, and CO_2 Emission

By selecting this switch, different calculations are executed for which the corresponding input data have to be defined. For example, if "Performance" is selected just the general data for the engine like displacement, the Full Load Characteristic and the Motoring Curve have to be defined.

Selection Button Temperature Model

Deactivated
Cold Start Correction
Others…

In this case no temperature calculation and no correction of the fuel consumption or the emissions will take place.

Selection Button Temperature Model
Deactivated
Cold Start Correction
Others…
The actual fuel consumption is multiplied with the cold start factor which is defined in the component vehicle. The factor can be defined for different cycles as a function of time. In the task (Cycle Run and Cruising), the switch 'Cold Start Correction' has to be activated.

Selection Button Temperature Model
Deactivated
Cold Start Correction
Others…
The temperature calculation, the correction of the fuel consumption or the emissions as well as the friction calculation will be executed.

Selection Button Temperature
Pre-defined Characteristic
Calculated
from Data Bus
The temperature of the engine is taken out of a pre-defined characteristic which depends on time.

Selection Button Temperature
Pre-defined Characteristic
Calculated
from Data Bus
The temperature of the engine is calculated.
Selection Button Temperature
Pre-defined Characteristic
Calculated
from Data Bus
When the engine temperature is calculated in an external component (Black Box, MATLAB®, Flowmaster) or the function component or defined in the general map, it can be transferred into the engine component through the Data Bus input channel 'Temperature External'.

Task and cycle dependent temperature characteristics can be defined in the vehicle and the actual temperature values can be made available on the Data Bus.

For this option, the switch 'Pre-defined Temperature Curve' has to be activated in the task (Cycle Run and Cruising).

Selection Button Consumption Model
Warm-up Enrichment
Enrichment by Increasing Friction Mean Pressure
Enrichment by Mean Pressure Factor
The warm-up enrichment is done by a characteristic which is defined as function of the temperature.

Selection Button Consumption Model
Warm-up Enrichment
Enrichment by Increasing Friction Mean Pressure
Enrichment by Mean Pressure Factor
The warm-up enrichment is done by a calculation of the increasing friction mean pressure due to a lower temperature.

Selection Button Consumption Model
Warm-up Enrichment
Enrichment by Increasing Friction Mean Pressure
Enrichment by Mean Pressure Factor
The warm-up enrichment is done by a calculation of a mean pressure factor which depends on the mean pressure of the warm and the cold engine.

Selection Button Friction Model
standard
advanced
The standard friction model is used in calculation. This option is only available if the switch **Temperature Model** is set to *Others...*

Selection Button Friction Model
standard
advanced
The advanced friction model is used in calculation. This option is only available if the switch **Temperature Model** is set to *Others...*

Selection Button Consumption/Emissions at Idle
Fixed Value
From Overall Map
From Idle Map
First Line from Overall Map
The consumption and the emissions at idle are as they are defined in the fixed values.

Selection Button Consumption/Emissions at Idle
Fixed Value
From Overall Map
From Idle Map
First Line from Overall Map
The consumption and the emissions at idle are calculated out of the overall maps for the fuel consumption and the emissions.

Selection Button Consumption/Emissions at Idle
Fixed Value
From Overall Map
From Idle Map
First Line from Overall Map
The consumption and the emissions at idle are calculated out of detailed maps for the fuel consumption and the emissions.

Selection Button Consumption/Emissions at Idle
Fixed Value
From Overall Map
From Idle Map
First Line from Overall Map
The data of the first line of the overall map is used for the calculation of the consumption/emission at idle.

Selection Button Motoring Curve Performance
From Motoring Curve
Synthetic
The defined Motoring Curve is used.

Selection Button Motoring Curve Performance
From Motoring Curve
Synthetic
The Motoring Curve is determined with an empirical formula.

Selection Button Motoring Curve Consumption/Emission
From Motoring Curve
Synthetic
Determine from
Consumption Map
In this case the defined Motoring Curve is used.

Selection Button Motoring Curve Consumption/Emission
From Motoring Curve
Synthetic
Determine from
Consumption Map
The Motoring Curve is determined with an empirical formula.

Selection Button Motoring Curve Consumption/Emission
From Motoring Curve
Synthetic
Determine from
Consumption Map
In this case the Motoring Curve is determined from the Fuel Consumption Map.

Switch Start Enrichment
When this switch is activated, an additional fuel injection takes place which can be defined as function of time.

Switch Acceleration Enrichment
When this switch is activated, an additional fuel injection takes place while acceleration can be defined as function of time.

Switch Additional FC External (Mass Flow)
If this switch is enabled an additional fuel consumption from the Data Bus input channel 'Additional FC (Mass Flow)' is added to the originally determined fuel consumption.

Switch FC Coefficient External
If this switch is enabled, the determined fuel consumption (inclusive additional external FC) is multiplied with the FC coefficient delivered by the Data Bus input channel 'FC Coefficient External.'

Selection Button Idle Speed
Fixed Value
From Idle Speed Characteristic
From Data Bus
In this case the idle speed is fixed on a constant value.

Selection Button Idle Speed
Fixed Value
From Idle Speed Characteristic
From Data Bus
In this case the idle speed can be defined as function of the engine temperature.

Selection Button Idle Speed
Fixed Value
From Idle Speed Characteristic
From Data Bus
In this case the idle speed will be read from the Data Bus.

Switch Idle Speed Control
If this switch is enabled the idle speed is controlled to the defined target idle speed.

Selection Button Maximum Speed
Fixed Value
From Data Bus
In this case the constant input value for maximum speed is taken.

Selection Button Maximum Speed
Fixed Value
From Data Bus
In this case the maximum speed will be read from the Data Bus.

Full Load Reduction
off
Factor
Characteristic
In this case nor reduction of the full load is made.

Full Load Reduction
off
Factor
Characteristic
In this case the full load reduction is made by a constant reduction factor.

Full Load Reduction
off
Factor
Characteristic
In this case the reduction is made by a characteristic. This characteristic can be defined as power, torque or BMEP versus speed.

Response Behavior Turbo Charger
deactivated
Constant Boost Pressure Build-up Time
Pressure Build-up Time from Characteristic
Constant BMEP Build-up Time
BMEP Build-up Time from Characteristic
In this case no delayed response behavior at the turbo charger is considered. Always the full boost pressure is available.

Response Behavior Turbo Charger
deactivated
Constant Boost Pressure Build-up Time
Pressure Build-up Time from Characteristic
Constant BMEP Build-up Time
BMEP Build-up Time from Characteristic
In this case the delayed response behavior of the turbo charger is considered by a constant boost pressure build-up time.

Response Behavior Turbo Charger
deactivated
Constant Boost Pressure Build-up Time
Pressure Build-up Time from Characteristic
Constant BMEP Build-up Time
BMEP Build-up Time from Characteristic
In this case the delayed response behavior of the turbo charger is considered by a variable boost pressure build-up time. The pressure build-up time can be defined as function of the engine speed.

Response Behavior Turbo Charger
deactivated
Constant Boost Pressure Build-up Time
Pressure Build-up Time from Characteristic
Constant BMEP Build-up Time
BMEP Build-up Time from Characteristic
In this case the delayed response behavior of the turbo charger is considered by a constant BMEP build-up time. This is the time which the engine takes between a user-defined BMEP start value (e.g., 2 bar) and a user-defined end value (in percentages of maximum BMEP at reference speed 1000 rpm; e.g., 90 %).

Response Behavior Turbo Charger
deactivated
Constant Boost Pressure Build-up Time
Pressure Build-up Time from Characteristic
Constant BMEP Build-up Time
BMEP Build-up Time from Characteristic
In this case the delayed response behavior of the turbo charger is considered by a variable BMEP build-up time. The BMEP build-up time can be defined as a function of the engine speed. It is the time which the engine takes between a user-defined BMEP start-value (e.g., 2 bar) and a user-defined end value (in percentages of maximum BMEP at user-defined speed; e.g., 90 %).

Turbo Charger Transfer Model
PT1-Behavior
PT2-Behavior
In this case the build-up behavior of the boost pressure is modeled by a PT1 filter.

Turbo Charger Transfer Model
PTl-Behavior
PT2-Behavior
In this case the build-up behavior of the boost pressure is modeled by a PT2 filter.

Switch Boost Pressure at Idle
When this switch is activated, the 'Boost Pressure at Idle' has to be defined in an input field in the section 'Turbo Charger/Boost Pressure.' One condition is that the selection button 'Response Behavior Turbo Charger' is set to 'Constant Boost Pressure Build-up Time' or to 'Pressure Build-up Time From Characteristic.'

Selection Button Testbed Power Correction
Deactivated
Standard
In this case no power correction is made.

Selection Button Testbed Power Correction
Deactivated
Standard

In this case a power correction on environment conditions is made. For this correction the standard 97/21/EG (April 1997) is used, which was originally developed for the standardization of power measurements.

Switch Specific Consumption Map
When this switch is activated the specific Fuel Consumption Map is active.

Switch Full Load Gear Dependent 1–5
For defined gear positions, extra Full Load Characteristics can be defined. They are used instead of the original ones.

Selection Button Full Load Reduction Gear Dependent
Off
Factor
From Characteristic
In this case the 'Full Load Reduction Characteristics' have no influence.

Selection Button Full Load Reduction Gear Dependent
Off
Factor
From Characteristic
In this case for every activated characteristic 'Full Load Gear Dependent 1,…,5' a reduction factor has to be defined. The values from the gear dependent characteristic are multiplied with this factor.

Selection Button Full Load Reduction Gear Dependent
Off
Factor
From Characteristic
In this case for every activated characteristic 'Full Load Gear Dependent 1,…,5' an additional 'Full Load Reduction Characteristic' has to be defined. The values from the reduction characteristic are subtracted from the gear dependent characteristic.

Switch Engine Brake Curve
This switch activates the engine brake curve. With this brake curve it is possible to simulate a jake brake system. This works with changing of the valve opening period, when the vehicle brakes. With the Data Bus input *Jake Brake Activation* the consideration of the brake curve can be controlled during calculation (1..activated, 0..deactivated).

Switch Starter Current
When this switch is activated, up to 5 temperature-dependent starter current characteristics can be used when the engine is started. Each characteristic is associated with a user-defined constant temperature value. An interpolation between these maps is done so that for every time step a current depending on the actual temperature can be determined.

Switch Load Signal Map
When this switch is activated the input throttle valve map is used. If this switch is deactivated the throttle valve map will be interpolated linear between the Full Load Characteristic and the Motoring Curve.

For all these settings different maps or input data are necessary. For not forcing the user to put in all data the ones which are not needed are shaded.

Selection Button Control Variable
Load Signal
Desired Torque
In this case the engine is controlled by the load signal which is supplied via Data Bus.

Selection Button Control Variable
Load Signal
Desired Torque
In this case the engine is controlled by the desired torque value which comes from the Data Bus.

2.9.1.1 Selection Button Exhaust System Model

Standard Exhaust System Model
Advanced AVL Exhaust System Model
This should be selected if the engine is connected to the standard 'Exhaust System' component and the selection button **intended for calculation of** is set to selections containing emission calculations.

Selection Button Exhaust System Model
Standard Exhaust System Model
Advanced AVL Exhaust System Model
This should be selected if the engine is connected to the 'AVL Exhaust System' component and the selection button **intended for calculation of** is set to selections containing emission calculations.

2.9.2 User-Defined Variables

Characteristic Data

$Z_{E,type}$	State indicator for engine type	–

This selection button has two positions:

- Gasoline
- Diesel

$Z_{E,charger}$	State indicator for charger type	–

This selection button has three positions:

- *Without*: For the power correction on environment conditions it can be selected that a naturally aspired engine is used.
- *Turbo Charger*: For the power correction on environment conditions it can be selected that a charged engine is used.
- *TC with Intercooler*: For the power correction on environment conditions it can be selected that a charged engine with intercooler is used.

$V_{E,h}$	Engine Displacement	cm^3

The engine displacement is the displacement of all cylinders together.

By choose a conversion on a different displacement can be done. In this case all torques and the absolute consumption and emission values are multiplied with the displacement ratio.

$T_{E,W}$	Engine Working Temperature	°C

The engine working temperature is needed for a calculation with hot start. If hot start is chosen the engine temperature at the beginning of the calculation is equal to the engine working temperature. If cold start is chosen the engine temperature at the beginning of the calculation is equal to the ambient temperature. This engine working temperature means always the temperature of the equivalent mass which is used for the calculation of the engine temperature.

$N_{E,c}$	Number of Cylinders	–
$N_{E,stroke}$	Number of Strokes (two-stroke 2, four-stroke 4)	–
Θ_E	Inertia Moment	km^2

The mass moment of inertia contains all parts of the engine like the crankshaft, the flywheel, a possible fan, the camshaft, and others.

$t_{E,add}$	Response Time	s

The response time is the time the engine needs to build up the full power.

$\dot{\varphi}_{E,max}$	Maximum Speed	rpm

It is possible to define a maximum speed for the engine. If the engine speed is above this speed the fuel injection will be stopped.

Fuel Type

$z_{E,fuel}$	Type of Fuel (denomination: diesel, gasoline, hydrogen, methanol, …)	–
$\rho_{E,fuel}$	Fuel Density	kg/m^3
$H_{E,fuel}$	Heating Value	kJ/kg
$z_{E,C}$	Weight Rate Carbon	–

Here the characteristic data of the fuel like the density or the heating value are input. They are used for temperature and emission calculations of the motor.

Idle

$\dot{\varphi}_{E,idle,base}$	Idle Speed	rpm

Here the fixed value for the idle speed can be defined. This value is used when the selection button **Idle Speed** is set to *Fixed Value.*

$b_{E,idle}$	Idle Fuel Consumption	l/h
$e_{E,NOx,idle}$	Idle NO_x Emission	kg/h
$e_{E,CO,idle}$	Idle CO Emission	kg/h
$e_{E,HC,idle}$	Idle HC Emission	kg/h
$e_{E,Soot,idle}$	Idle Soot Emission	kg/h

Here the fixed values for the idle consumption and the idle emissions can be defined.

These values are used when the selection button **Consumption/Emissions at Idle** is set to fixed value.

Fuel Shut-Off

The fuel shut-off is used to switch off the fuel injection while the engine is in thrust operation. With this the fuel consumption can be decreased.

Selection Button Fuel Shut-Off

Absolute Speed Limits

This activates the definition of absolute lower and upper speed values for fuel shut-off.

Relative Speed Differences

Selection of this option activates the input fields ‘Speed Difference above Idle Speed for Lower Speed Limit’ and ‘Speed Difference above Idle Speed for Upper Speed Limit.’

With these speed difference definitions, a definition of the speed limits relative to the idle speed can be done.

This is useful if the idle speed is not fixed to a constant value during the calculation, e.g., when a temperature-dependent idle speed characteristic is used.

Cut-Off Signal from Data Bus

The user can create his own cut-off control and connect the cut-off signal via Data Bus to the engine component via the new Data Bus input 'Fuel Shut-Off Activation.'

When the Engine is in thrust mode and the Data Bus signal is not equal to zero, the engine is set to cut-off mode and the 'Residual Fuel Consumption' is taken for the consumption calculation. In all other cases, the engine is not in cut-off mode.

$\dot{\varphi}_{E,SA,low}$	Lower Speed Border for Fuel Shut-Off	rpm
$\dot{\varphi}_{E,SA,high}$	Upper Speed Border for Fuel Shut-Off	rpm
$\dot{\varphi}_{E,SA,low,rel}$	Speed Difference Above Idle Speed for Lower Speed Limit	rpm
$\dot{\varphi}_{E,SA,high,rel}$	Speed Difference Above Idle Speed for Upper Speed Limit	rpm
$b_{E,SA}$	Residual Fuel Consumption	l/h
$z_{E,SA,fc}$	Consumption Increase After Deactivation (linear/sharp rise)	–

Comments

Engine-specific information can be entered, stored, and viewed in a 'comments' table. The table consists of the columns 'Description | Value | Unit.' When adding a row to the table, the window of a global, 'pre-defined' comments table appears.

In the first step, definitions for the pre-defined comments table have to be done in the form 'Attribute | Description | Data Type | Unit.'

In the second step, rows from this global table can be selected to be added as rows in the engine-specific comments table for the actual engine.

Friction Mean Effective Pressure (FMEP)

$T_{E,N}$	Nominal Temperature	°C
$m_{E,eq}$	Equivalent Mass	kg
$z_{E,EE}$	Exhaust Proportion of Waste Energy	–

Standard Friction Model

$p_{E,fric,min}$	FMEP at Minimum Engine Speed	bar
$p_{E,fric,max}$	FMEP at Maximum Engine Speed	bar
$c_{E,fric,exp}$	Exponent of FMEP Characteristic	–
$c_{E,fric,p}$	Curvature Factor	–
$\eta_{E,40}$	Dynamic oil Viscosity at 40 °C	Pa s

Advanced Friction Model

Selection Button Friction Model

PNH Model

SLM Model

With this selection button either the PNH model or the SLM model can be chosen.

$C_{E,bore}$	Bore	mm
$C_{E,hub}$	Hub	mm
$r_{E,compress}$	Compression Ratio	–

Selection Button Engine Layout

User specified

Typical in-line

Typical 6 Cylinder V

Typical 8 Cylinder V

Engine Layout User Specified

$d_{E,crsft,bearing}$	Crankshaft Main Bearing Diameter	mm
$l_{E,crsft,bearing}$	Crankshaft Main Bearing Length	mm
$n_{E,crsft,bearings}$	Number of Crankshaft Main Bearings	–
$d_{E,conRod,bearing}$	Big End Con Rod Bearing Diameter	mm
$l_{E,conRod,bearing}$	Big End Con Rod Bearing Length	mm

Selection Button Type of Valve Train

No Valve Train

SOHC Finger Follower

SOHC Rocker Arm

SOHC direct acting

DOHC direct acting

OHV Push Rods

With this selection button the type of the valve train can be specified.

$n_{E,valves,intake}$	Number of Intake Valves Per Cylinder	–
$n_{E,valves,exhaust}$	Number of Exhaust Valves Per Cylinder	–
$C_{E,valve,liftMax}$	Maximum Valve Lift	mm

Selection Button Type of Cam Follower Flat Follower

Roller Follower

$n_{E,cmsft,bearings}$	Number of camshaft bearings	–

Selection Button Used Engine Oil

SAE 10/20/30/40

SAE 0W/30/0W/40

SAE 5W/30/5W/40

SAE 10W/30/10W/40/10W/60
SAE 15W/30

Selection Button Fuel Injection Pump installed

no
yes

Pre-defined Temperature Curve

$T_{E(t)}$	Engine Temperature	°C

Here the temperature characteristic of the engine can be defined by the user.

Cooling Characteristic

$c_{E,v,cool}(T_E)$	Heat Capacity	J/K

The cooling characteristic is used for the determination of the amount of heat which is lost to the environment.

The heat capacity has to be given as a function of the actual temperature of the engine.

Warm-up Enrichment

$\Delta b_{E,warm\text{-}up,enrich}(T_E)$	Consumption enrichment during warm-up	l/h

The warm-up enrichment is defined as function of the engine temperature.

Start Enrichment

$\Delta b_{E,start,enrich}(t)$	Consumption enrichment during the first time after starting	l/h

The start enrichment is defined as function of time. The start enrichment can be switched on and off with the switch for the start enrichment.

Acceleration Enrichment

$\Delta b_{E,acc,enrich}(\dot{\alpha}_{th})$	Consumption enrichment during acceleration	l/h

The acceleration enrichment can be defined as function of the throttle valve speed.

It is used to inject additional fuel during stepping on the acceleration pedal. The acceleration enrichment can be switched on and off with the switch for the acceleration enrichment.

Idle Speed Characteristic

$\dot{\boldsymbol{\varphi}}_{\mathbf{E,idle}}(\boldsymbol{T}_{\mathbf{E}})$	Idle Speed	rpm

Here the idle speed can be defined as function of the engine temperature. This characteristic is only active when the selection button **Idle Speed** is set to *From Idle Speed Characteristic.*

Boost Pressure Build-up Time

$t_{\mathrm{E,ch,build\text{-}up}}$	Constant Boost Pressure Build-up Time	s

or

$t_{\mathrm{E,ch,build\text{-}up}}\ (\dot{\boldsymbol{\varphi}}_{\mathbf{E,out}})$	Boost Pressure Build-up Time as Function of Speed	s

This is the time the charger needs to build up the full boost pressure.

Boost Pressure

$p_{\mathrm{E,ch,idle}}$	Boost Pressure at Idle	bar

This value is required if the option "Boost Pressure at Idle" in the Properties window is activated.

$p_{\mathrm{E,ch}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Boost Pressure as absolute pressure	bar

The boost pressure has to be defined as absolute pressure dependent on the engine speed.

BMEP Build-up Time

$t_{\mathrm{E,ch,BMEP,start}}$	BMEP at Build-up Start	bar

This is the engines BMEP at begin of BMEP build-up time.

$t_{\mathrm{E,ch,BMEP,stop}}$	BMEP after Build-up Time, as percentages of maximum BMEP	%

This is the engines BMEP at the end of BMEP build-up time. It has to be defined as percentages of maximum BMEP at a certain speed. This speed is user-defined (in case that build-up time as function of speed is chosen), otherwise (when constant build-up time is chosen) a reference speed of 1000 rpm is considered.

$t_{\mathrm{E,ch,build\text{-}upBMEP}}$	Constant BMEP Build-up Time	s

This value has to be defined if the selection button **Response Behavior Turbo Charger** is set to *Constant BMEP Build-up Time.*

$t_{\mathrm{E,ch.build-upBMEP}}(\dot{\varphi}_{\mathrm{E,out}})$	BMEP Build-up Time as function of speed	s

This value has to be defined if the selection button **Response Behavior Turbo Charger** is set to *BMEP Build-up Time From Characteristic.*

Charger Outlet Temperature

$\boldsymbol{t_{\mathrm{E,ch}}(\dot{\varphi}_{\mathrm{E,out}})}$	Temperature behind charger	°C

The temperature behind charger has to be defined as function of the engine speed.

Cooler Outlet Temperature

$t_{\mathrm{E,IC}}(\dot{\varphi}_{\mathrm{E,out}})$	Temperature behind intercooler	°C

The temperature behind intercooler has to be defined as function of the engine speed.

Basic Idle Maps

Idle Consumption Map

$\boldsymbol{b_{\mathrm{E,idle}}(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}})}$	Idle Consumption Map	l/h or kg/h

The idle consumption map is defined as function of the brake mean pressure with the engine speed as parameter. It is only used when the selection button **Consumption/Emissions at Idle** is set to *From Idle Map.*

Idle Emission Maps

$e_{\mathrm{E,idle,NO_X}}(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}})$	Idle Emission Map NO_x	kg/h
$e_{\mathrm{E,idle,CO}}(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}})$	Idle Emission Map CO	kg/h
$e_{\mathrm{E,idle,HC}}(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}})$	Idle Emission Map HC	kg/h
$e_{\mathrm{E,idle,Soot}}(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}})$	Idle Emission Map Soot	kg/h

The idle emission maps are defined as function of the brake mean pressure with the engine speed as parameter. They are only used when the selection button **Consumption/Emissions at Idle** is set to *From Idle Map.*

Extended Idle Maps

The following maps are only used when the selection button **Consumption/ Emissions at Idle** is set to *From Idle Map* and the selection button **Exhaust System Model** is set to *Advanced AVL Exhaust System Model*.

$e_{E,idle,O_2}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Emission Map O_2	kg/h
$e_{E,idle,H_2O}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Emission Map H_2O	kg/h
$e_{E,idle,CO_2}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Emission Map CO_2	kg/h
$e_{E,idle,H_2}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Emission Map H_2	kg/h

The idle emission maps are defined as a function of the brake mean pressure with the engine speed as parameter.

$e_{E,idle,exh}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Exhaust Mass Flow Characteristic	kg/h
$T_{E,idle,exh}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Idle Exhaust Temperature Characteristic	°C

In the idle exhaust temperature characteristic the temperature is listed dependent on the mean pressure with the engine speed as parameter.

Basic Engine Maps

Fuel Consumption Maps

Absolute Consumption Map

$b_{E,h}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Fuel Consumption Map	l/h or kg/h

At the Fuel Consumption Map the actual fuel consumption for stationary operation is listed depending on the brake mean pressure with the engine speed as parameter. This kind of representation is used to make a unique relation between the brake mean pressure and the fuel consumption for a given engine speed.

For the idle consumption there are different possibilities. By choose it can be interpolated out of the Fuel Consumption Map or the defined value is used. If the mean pressure is out of the defined range the corresponding values are extrapolated.

Specific Consumption Map

$b_{E,spec}\left(\dot{\varphi}_{E,out}, p_{eff}\right)$	Specific Fuel Consumption Map	l/kWh or kg/kWh

The Fuel Consumption Map can also be defined as Specific Consumption Map. By a switch the Specific Consumption Map can be converted into the absolute one. The Specific Consumption Map is only used when the corresponding switch is activated.

Both maps can also be represented in iso-lines, where all three input values can be used as parameter of the representation.

Emission Maps

$e_{E,NO_X}(\dot{\varphi}_{E,out}, p_{eff})$	NO_x Emission Map	kg/h
$b_{E,CO}(\dot{\varphi}_{E,out}, p_{eff})$	CO Emission Map	kg/h
$b_{E,HC}(\dot{\varphi}_{E,out}, p_{eff})$	HC Emission Map	kg/h
$b_{E,Soot}(\dot{\varphi}_{E,out}, p_{eff})$	Soot Emission Map	kg/h

In the emission maps the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter.

Extended Engine Maps

The following maps are only used when the selection button **Exhaust System Model** is set to *Advanced AVL Exhaust System Model*.

$e_{E,O_2}(\dot{\varphi}_{E,out}, p_{eff})$	O_2 Emission Map	kg/h
$e_{E,H_2O}(\dot{\varphi}_{E,out}, p_{eff})$	H_2O Emission Map	kg/h
$e_{E,CO_2}(\dot{\varphi}_{E,out}, p_{eff})$	CO_2 Emission Map	kg/h
$e_{E,H_2}(\dot{\varphi}_{E,out}, p_{eff})$	H_2 Emission Ma	kg/h

In the emission maps the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter.

$e_{E,exhaust}(\dot{\varphi}_{E,out}, p_{eff})$	Exhaust Mass Flow Characteristic	kg/h
$T_{E,exhaust}(\dot{\varphi}_{E,out}, p_{eff})$	Exhaust Temperature Characteristic	°C

In the exhaust temperature characteristic the temperature is listed dependent on the mean pressure with the engine speed as parameter.

Full Load Characteristic

Test Environment

$p_{E,env,dyno}$	Air Pressure at the test bench run	bar
$T_{E,env,dyno}$	Air Temperature at the test bench run	°C
$\rho_{E,W,env,dyno}$	Absolute Humidity at the test bench run	kg/m^3

The environment conditions at the test bench run are used for the power correction on environment conditions.

Full Load Characteristic optionally:

$P_{E,vk}(\dot{\varphi}_{E,out})$	Full Load Characteristic as power	W

or

$M_{E,vk}(\dot{\varphi}_{E,out})$	Full Load Characteristic as torque	Nm

or

$p_{E,eff,vk}(\dot{\varphi}_{E,out})$	Full Load Characteristic as BMEP	bar

The full load characteristic can be defined either as power, as torque or as brake mean pressure dependent on the engine speed.

Full Load Reduction

Constant Reduction Factor

$z_{E,red}$	Reductions Factor	–

The Full Load Characteristic is multiplied with this factor over the whole speed range.

Full Load Reduction Characteristic optional:

$P_{E,vk,red}(\dot{\varphi}_{E,out})$	Full Load Reduction Characteristic as power	W

or

$M_{E,vk,red}(\dot{\varphi}_{E,out})$	Full Load Reduction Characteristic as torque	Nm

or

$p_{E,eff,vk,red}(\dot{\varphi}_{E,out})$	Full Load Reduction Characteristic as BMEP	bar

The full load reduction characteristic is subtracted from the original Full Load Characteristic.

Full Load Gear Dependent 1–5

$N_{E,vk,geardep,i,low}$	Lowest Gear Position for which the gear dependent Full Load Characteristic is active	–
$N_{E,vk,geardep,i,high}$	Highest Gear Position for which the gear dependent Full Load Characteristic is active	–

Lowest and highest gear position has to be defined for every activated gear dependent Full Load Characteristic.

Optionally:

$P_{E,vk,red,i}(\dot{\varphi}_{E,out})$	Gear dependent Full load 1–5 as power	W

or

$M_{E,vk,red,i}(\dot{\varphi}_{E,out})$	Gear dependent Full Load 1–5 as torque	Nm

or

$p_{\mathrm{E,eff,vk,red,i}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Gear dependent Full Load 1–5 as BMEP	bar

The gear dependent Full Load Characteristics can be defined separately for the single gears either as power, as torque or as brake mean pressure dependent on the engine speed.

If one gear is associated with more than one of the five maps, then the first associated map is used for calculation.

Gear Dependent Full Load Reduction Characteristic 1–5

Constant gear dependent Reduction Factor 1–5:

$z_{\mathrm{E,red,geardep}}$	Reduction Factor	–

The associated gear dependent Full Load Characteristic is multiplied with this factor over the whole speed range.

$P_{\mathrm{E,vk,red,geardep}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Gear dependent Full Load Reduction Characteristic 1–5	W

The gear dependent full load reduction characteristics are subtracted from the associated gear dependent Full Load Characteristics.

Motoring Curve

Optionally:

$P_{\mathrm{E,sk}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Motoring Curve as power	W

or

$M_{\mathrm{E,sk}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Motoring Curve as torque	Nm

or

$p_{\mathrm{E,eff,sk}}\left(\dot{\varphi}_{\mathrm{E,out}}\right)$	Motoring Curve as BMEP	bar

In the Motoring Curve, the friction of the engine is described considering the idle torque the engine can deliver at the special engine speed. The Motoring Curve can be defined similar to the Full Load Characteristic either as power, as torque or as brake mean pressure dependent on the engine speed.

Engine Brake Curve
Optional:

$P_{\mathrm{E,plc}}\left[\omega_{\mathrm{E,out}}\right]$	Engine Brake Curve as power	W

or

$M_{\mathrm{E,plc}}\left[\omega_{\mathrm{E,out}}\right]$	Engine Brake Curve as torque	Nm

or

$p_{\mathrm{E,plc}}\left[\omega_{\mathrm{E,out}}\right]$	Engine Brake Curve as mean pressure	Pa

In the engine brake curve, the back pressure of the engine is described considering the brake torque the engine can deliver in the case of a braking. The power loss curve can be defined similar to the load characteristic either as power, as torque or as brake mean pressure dependent on the engine speed.

With the Data Bus input *Jake Brake Activation* the consideration of the brake curve can be controlled during calculation (1…activated, 0…deactivated).

Starter Current

$\boldsymbol{I}_{\mathbf{E,start,i}}(t)$	Sequence of the Starter Current at the starting process, defined for up to 5 temperature levels	A

The starter current characteristics are used for the start-stop automatic (if this special component is used).

For each characteristic a temperature level has to specified; the current is defined depending on time.

Load Signal Map

$\alpha_{\mathrm{E,th}}\left(\dot{\varphi}_{\mathrm{E,out}}, p_{\mathrm{eff}}\right)$	Load Signal Map	%

The throttle valve positions can be defined dependent on the engine speed and the brake mean pressure.

2.9.3 Input and Output Variables

2.9.3.1 Mechanical Connections

$\dot{\varphi}_{E,out}$	Engine angular velocity on the power take-off side	rad/s
$\ddot{\varphi}_{E,out}$	Engine angular acceleration on the power take-off side	rad/s^2
$M_{E,out}$	Engine torque on the power take-off side	Nm

2.9.3.2 Input Values

$\alpha_{E,th}$	Load Signal	–
$K_{E,start}$	Start Switch	–
$Q_{E,Q}$	Battery Charge	A s
T_E	Temperature external	K
$K_{E,activ}$	Engine Activation	–
$\dot{\varphi}_{E,idle}$	Idle Speed	rad/s
$K_{E,jake\ brake}$	Jake Brake Activation	–
$M_{E,desired}$	Desired Torque	Nm
$\dot{\varphi}_{E,max}$	Maximum Speed	rad/s
$b_{E,add}$	Additional FC (Mass Flow)	kg/s
$b_{E,coeff,ext}$	FC Coefficient External	–
$K_{E,shut-off}$	Fuel Shut-Off Activation	–

2.9.3.3 Output Values

$\alpha_{E,th}$	Actual Load Signal	–
$b_{E,h,act}$	Fuel Consumption (Volume Flow, instantaneous)	m^3/s
$P_{E,emis}$	Exhaust Gas Energy	W
$e_{E,NOx,act}$	Emission NO_x (instantaneous)	kg/s
$e_{E,CO,act}$	Emission CO (instantaneous)	kg/s
$e_{E,HC,act}$	Emission HC (instantaneous)	kg/s
$e_{E,soot,act}$	Emission Soot (instantaneous)	kg/s
$e_{E,CO_2,act}$	Emission CO_2 (instantaneous)	kg/s
$e_{E,H_2,act}$	Emission H_2 (instantaneous)	kg/s
$e_{E,O_2,act}$	Emission O_2 (instantaneous)	kg/s
$e_{E,H_2O,act}$	Emission H_2O (instantaneous)	kg/s
T_E	Engine Temperature (instantaneous)	K
$K_{E,operate}$	Operation Control	–

(continued)

$\dot{\varphi}_{E,out}$	Speed	rad/s
$M_{E,pre}$	Torque before Flywheel	Nm
$M_{E,post}$	Torque behind Flywheel	Nm
P_E	Engine Power	W
$e_{E,exhaust}$	Exhaust Mass Flow	kg/s
$T_{E,exhaust}$	Exhaust Temperature	K
$b_{E,massFlow,act}$	Fuel Consumption (Mass Flow, instantaneous)	kg/s
p_E	BMEP	Pa
$P_{E,loss}$	Power Loss	W

2.9.4 Computation Variables

$p_{eff,vk}$	Brake mean pressure at full load curve for $\dot{\varphi}_{E,out}$	Pa
$p_{eff,sk}$	Brake mean pressure at Motoring Curve for $\dot{\varphi}_{E,out}$	Pa
$p_{E,env,dry,dyno}$	Dry Pressure of the environment on the test bench	Pa
R_{Wet}	Gas Constant of the wet air	J/kg K
$T_{E,inlet,dyno}$	Air Temperature at the inlet on the test bench	K
$p_{E,inlet,dyno}$	Dry pressure at the inlet on the test bench	Pa
$\eta_{E,ch}$	Charger Efficiency	–
$\eta_{E,IC}$	Intercooler Efficiency	–
$T_{E,Mot}$	Temperature in the power house at the actual driving conditions	K
$p_{E,Mot,dry}$	Dry Pressure in the power house at the actual driving conditions	Pa
$T_{E,inlet,act}$	Air Temperature at the inlet at the actual driving conditions	K
$p_{E,inlet,act}$	Dry pressure at the inlet at the actual driving conditions	Pa
$p_{E,ch,over,dyno}$	Dry Over Pressure of the charger at the test bench	Pa
$p_{E,ch,over,act}$	Dry Over Pressure of the charger at the actual driving conditions	Pa
$p_{E,ch,act}$	Dry Absolute Pressure behind the charger at the actual driving conditions	Pa
$T_{E,ch,act}$	Air Temperature behind the charger at the actual driving conditions	K
F_A	Atmospheric Correction Factor	–
f_m	Engine Factor	–
$\alpha_{pow,corr}$	Power Correction Factor	–
$p_{eff,theo}$	Actual brake mean pressure out of engine map for instantaneous throttle position	Pa
$p_{eff,theo,old}$	Brake mean pressure for the last time step	Pa
$p_{eff,max}$	Maximum brake mean pressure	Pa
$P_{E,heat}$	Heat produced by combustion	W
$P_{E,cool}$	Energy flow in the cooling system	W

(continued)

α_A	Actual heat capacity	W/K
$p_{E,fric,ref}$	Reference friction mean pressure	Pa
$\eta_{E,act}$	Dynamic oil viscosity at actual engine temperature	Pa.s
$\eta_{E,ref}$	Dynamic oil viscosity at ref. temperature	Pa.s
$p_{E,fric,add}$	Additional mean pressure caused by friction	Pa
$M_{E,fric}$	Friction torque of engine	Nm
$p_{eff,loss}$	Brake mean pressure at power loss curve for $\dot{\varphi}$	Pa

2.9.5 Equation System

2.9.5.1 Conversion of the Full Load Characteristic

A given Full Load Characteristic as power results in the corresponding characteristic of moments [2]:

$$M_{E,vk} = \frac{P_{E,vk}}{\dot{\varphi}_{E,out}} \tag{2.9.1}$$

or as mean effective pressure [2]:

$$p_{eff,vk} = \frac{P_{E,vk} \cdot N_{E,stroke} \cdot \pi}{V_{E,h} \cdot \dot{\varphi}_{E,out}} \tag{2.9.2}$$

A given Full Load Characteristic as moment results in the corresponding characteristic as power [2]:

$$P_{E,vk} = M_{E,vk} \cdot \dot{\varphi}_{E,out} \tag{2.9.3}$$

or as mean effective pressure from equation.

If the Full Load Characteristic is adopted from the throttle valve map, the corresponding maximum values for the mean effective pressure will be iteratively assigned to the single angular velocities. In this context, it should be noted that a subsequent consideration by means of the editor of characteristic curves seems to be all the more useful the less the single maps are defined.

The same formula can be used for the Motoring Curve.

Inside the calculation kernel everything is calculated in mean effective pressure.

2.9.5.2 Reduced Full Load Characteristic

Constant reduction factor

The whole full load curve is multiplied with this factor [2].

$$p_{\mathrm{eff,vk}} = p_{\mathrm{E,eff,vk}} \cdot z_{\mathrm{E,red}} \tag{2.9.4}$$

Reduction curve

The reduction curve is subtracted from the full load curve [2].

$$p_{\mathrm{eff,vk}} = p_{\mathrm{E,eff,vk}} - p_{\mathrm{E,eff,vk,red}} \tag{2.9.5}$$

Reduced full load curve

If there exists a special full load curve for the selected gear then this curve is used instead of the original one [2].

$$N_{\mathrm{E,vk,red,i,high}} < N_{\mathrm{G,act}} < N_{\mathrm{E,vk,red,i,high}} \tag{2.9.6}$$

$$p_{\mathrm{eff,vk}} = p_{\mathrm{E,eff,vk,red,i}} \tag{2.9.7}$$

2.9.5.3 Interpolation of Full Load Characteristic and Motoring Curve for the actual engine speed

(a) for an engine speed lower than idle speed $\left(\dot{\varphi}_{\mathrm{E,out}} < \dot{\varphi}_{\mathrm{E,idle}}\right)$ [2]:

$$k_{\mathrm{E,operate}} = -1 \tag{2.9.8}$$

linear interpolation of $p_{\mathrm{E,vk,help}}$ and $p_{\mathrm{E,sk,help}}$ for $\dot{\varphi}_{\mathrm{E,idle}}$ [2]:

$$\Delta p = p_{\mathrm{E,vk,help}} - p_{\mathrm{E,sk,help}} \tag{2.9.9}$$

$$p_{\mathrm{eff,sk}} = -\frac{\Delta p}{\dot{\varphi}_{\mathrm{E,idle}}} \cdot f_{\mathrm{E,sk}} \cdot \dot{\varphi}_{\mathrm{E,out}} + p_{\mathrm{E,sk,help}} + \Delta p \cdot f_{\mathrm{E,sk}} \tag{2.9.10}$$

$$p_{\mathrm{eff,vk}} = p_{\mathrm{eff,sk}} + \frac{\Delta p}{\dot{\varphi}^3_{\mathrm{E,idle}}} \cdot \left(f_{\mathrm{E,sk}} - 1\right) \cdot \dot{\varphi}^3_{\mathrm{E,out}} - \frac{\Delta p}{\dot{\varphi}^2_{\mathrm{E,idle}}} \cdot \left(f_{\mathrm{E,sk}} - 2\right) \cdot \dot{\varphi}^2_{\mathrm{E,out}} \tag{2.9.11}$$

$$f_{\mathrm{E,sk}} = 1 (f_{\mathrm{E,sk}} = 4 \text{ for automatic structure}) \tag{2.9.12}$$

(b) for an engine speed higher than maximum speed $\left(\dot{\varphi}_{\mathrm{E,out}} > \dot{\varphi}_{\mathrm{E,max}}\right)$ [2]:

$$k_{\mathrm{E,operate}} = 1 \tag{2.9.13}$$

linear interpolation of $p_{\mathrm{E,vk,help}}$ and $p_{\mathrm{E,sk,help}}$ for $\dot{\varphi}_{\mathrm{E,max}}$ [2]:

$$p_{\mathrm{eff,vk}} = p_{\mathrm{E,vk,help}} - \left|\dot{\varphi}_{\mathrm{E,max}} - \dot{\varphi}_{\mathrm{E,out}}\right| \cdot \frac{N_{\mathrm{E,stroke}} \cdot \pi}{V_{\mathrm{E,h}}} \tag{2.9.14}$$

$$p_{\mathrm{eff,sk}} = p_{\mathrm{E,sk,help}} - \left|\dot{\varphi}_{\mathrm{E,max}} - \dot{\varphi}_{\mathrm{E,out}}\right| \cdot \frac{N_{\mathrm{E,stroke}} \cdot \pi}{V_{\mathrm{E,h}}} \cdot f_{\mathrm{E,sk}} \tag{2.9.15}$$

$$f_{\mathrm{E,sk}} = 1 \, (f_{\mathrm{E,sk}} = 0 \quad \text{for automatic structure}) \tag{2.9.16}$$

(c) for normal operating conditions $\left(\dot{\varphi}_{\mathrm{E,idle}} < \dot{\varphi}_{\mathrm{E,out}} < \dot{\varphi}_{\mathrm{E,max}}\right)$ [2]:

$$k_{\mathrm{E,operate}} = 0 \tag{2.9.17}$$

linear interpolation of $p_{\mathrm{eff,vk}}$ and $p_{\mathrm{eff,sk}}$ for $\dot{\varphi}_{\mathrm{E,out}}$

2.9.6 Power Correction on Environment Conditions

The power correction on environment conditions serves for the correction of the Full Load Characteristic when the environment conditions the user puts in are different from the conditions on the test bench. In this case a correction is made at which the standard 97/21/EG (April 1997) is used, which was originally developed for the standardization of power measurements.

For the power correction two selection buttons are used:

Selection Button Engine Type

Gasoline
Diesel

Selection Button Charger Type

Without
Turbo Charger
TC with Intercooler

With these selection buttons the factors for the power correction are fixed and the needed input maps and characteristics are activated.

To make a power correction, the standard conditions must first be defined.

These are called environment conditions during test bench run in the page of the Full Load Characteristic. If a charger or an intercooler is used the corresponding characteristics for the charger pressure the temperature behind charger and the temperature behind the intercooler have to be defined too. With these values the conditions at the inlet for the test bench run and the efficiencies for the charger and the intercooler can be calculated.

With the characteristics for the charger and the intercooler efficiency, the actual inlet conditions can be calculated out of the actual environment conditions by considering the temperature and pressure differences between the environment and the power house.

With the actual inlet conditions and the ones on the test bench the correction factors can be calculated and the Full Load Characteristic can be corrected.

(a) **Inlet Conditions on the test bench**

First the dry pressure of the environment at the test bench is calculated [2]:

$$p_{\mathrm{E,env,dry,dyno}} = p_{\mathrm{E,env,dyno}} - R_{\mathrm{Wet}} \cdot T_{\mathrm{E,env,dyno}} \cdot \rho_{\mathrm{E,W,env,dyno}} \tag{2.9.18}$$

with R_{Wet} = 461,521 J/kg K

These conditions are also the inlet conditions [2]:

$$T_{\mathrm{E,inlet,dyno}} = T_{\mathrm{E,env,dyno}} \tag{2.9.19}$$

$$p_{\mathrm{E,inlet,dyno}} = p_{\mathrm{E,env,dry,dyno}} \tag{2.9.20}$$

(b) **Inlet Conditions at the Actual Driving Conditions**

First, the under the hood conditions have to be calculated [2]:

$$T_{\mathrm{E,Mot}} = T_{\mathrm{U,air}} + T_{\mathrm{E,diff,ub}} \tag{2.9.21}$$

$$p_{\mathrm{E,Mot,dry}} = p_{\mathrm{U,air}} + p_{\mathrm{E,diff,ub}} - R_{\mathrm{Wet}} \cdot T_{\mathrm{E,Mot}} \cdot \rho_{\mathrm{U,W}} \tag{2.9.22}$$

The absolute humidity at environment conditions is calculated from the relative humidity using the following formulae [2]:

$$\rho_{\mathrm{U,W}} = \frac{\varphi_{\mathrm{U,air}} \cdot p_{\mathrm{W}}{}'}{R_{\mathrm{Wet}} \cdot T_{\mathrm{U,air}}} \tag{2.9.23}$$

with [2]:

$$p'_{\mathrm{W}} = 9.80665.e^{\left(58.73895 - \frac{6852.493}{T_{\mathrm{U,air}}} - 5.262.\ \ln T_{\mathrm{U,air}}\right)} \tag{2.9.24}$$

These underhood conditions are equal to the inlet conditions [2]:

$$T_{\mathrm{E,inlet,act}} = T_{\mathrm{E,Mot}} \tag{2.9.25}$$

$$p_{\mathrm{E,inlet,act}} = p_{\mathrm{E,Mot,dry}} \tag{2.9.26}$$

(c) **Correction Factors**
With the actual inlet conditions and the ones on the test bench the correction factors can be calculated.

- *Atmospheric Correction Factor* [2]:

$$f_{\mathrm{A}} = A \cdot \left(\frac{p_{\mathrm{E,inlet,act}}}{p_{\mathrm{E,inlet,dyno}}}\right)^{X} \cdot \left(\frac{T_{\mathrm{E,inlet,dyno}}}{T_{\mathrm{E,inlet,act}}}\right)^{Y} + B \tag{2.9.27}$$

  where the factors A, B, X, and Y depend on the engine and charger type.
- *Engine Factor*:
  - For gasoline engines [2]:

$$f_{\mathrm{m}} = 1 \tag{2.9.28}$$

  - For diesel engines [2]:

Correct fuel delivery parameter [2]:

$$q_c = \frac{p_{\mathrm{E,Mot}}}{p_{\mathrm{E,inlet,act}}} \cdot 1000 \cdot \pi \cdot \frac{N_{\mathrm{E,stroke}} \cdot b_{\mathrm{E,h,act}}}{V_{\mathrm{E,h}} \cdot \dot{\varphi}_{\mathrm{E,out}}} \tag{2.9.29}$$

$$\begin{gathered}(q_{\mathrm{c}} < 40) \rightarrow f_{\mathrm{m}} = 0.3 \\ (40 \leq q_{\mathrm{c}} \leq 65) \rightarrow f_{\mathrm{m}} = 0.036 \cdot q_{\mathrm{c}} - 1.14 \\ (q_{\mathrm{c}} > 65) \rightarrow f_{\mathrm{m}} = 1.2\end{gathered} \tag{2.9.30}$$

- *Power Correction Factor* [2]:

$$\alpha_{\mathrm{pow,corr}} = f_{\mathrm{A}}{}^{f_{\mathrm{m}}} \tag{2.9.31}$$

(d) **Power Correction**
With this power correction factor the Full Load Characteristic of the engine is reduced [2]:

$$p_{\mathrm{eff,vk}} = p_{\mathrm{eff,vk}} \cdot \alpha_{\mathrm{pow,corr}} \tag{2.9.32}$$

Evaluation of the engine torque as function of the throttle position [2]:
$\alpha_{E,th} = 0 \rightarrow$ Motoring Curve
$\alpha_{E,th} = 1 \rightarrow$ Full Load Characteristic

$$p_{eff,theo} = p_{eff,sk} + \left(p_{eff,vk} - p_{eff,sk}\right) \cdot \alpha_{E,th} \tag{2.9.33}$$

Response Time [2]

If $\left(\boldsymbol{p_{eff,theo} > p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}}}\right)$

$$p_{eff,theo} = p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}} \tag{2.9.34}$$

2.9.7 Charger Response Behavior

The charger response behavior works very similar to the power correction. Also a comparison between different inlet conditions is made. These conditions are the condition with delayed response of the turbo charger and an infinite response. The infinite response means that always the full boost pressure for this speed is available.

The correction is made with the same basis as the power correction, i.e., also the correction parameters form the standard 97/21/EG (April 1997) are used.

The calculation of the charger response behavior is done after the power correction.

For the calculation without power correction the boundary conditions are defined by the chassis dynamometer [2]:

$$T_{E,env,dyno} \quad \text{defined} \tag{2.9.35}$$

$$p_{E,env,dry,dyno} \quad \text{defined} \tag{2.9.36}$$

$$T_{E,Mot} = T_{E,env,dyno} \tag{2.9.37}$$

$$p_{E,Mot,dry} = p_{E,env,dry,dyno} \tag{2.9.38}$$

For calculation with power correction the conditions from the engine trunk has to be used [2]:

$$T_{E,Mot} \quad \text{from power correction} \tag{2.9.39}$$

$$p_{\mathrm{E,Mot,dry}} \quad \text{from power correction} \tag{2.9.40}$$

$$T_{\mathrm{E,env,dyno}} = T_{\mathrm{E,Mot}} \tag{2.9.41}$$

$$p_{\mathrm{E,env,dry,dyno}} = p_{\mathrm{E,Mot,dry}} \tag{2.9.42}$$

The boost pressure increases after a response time, which is calculated as followed [2]:

$$p_{\mathrm{E,ch,over,dyno}} = p_{\mathrm{E,inlet,dyno}} - \left(p_{\mathrm{E,env,dyno}} - R_{\mathrm{Wet}} \cdot T_{\mathrm{E,inlet,dyno}} \cdot \rho_{\mathrm{E,W,env,dyno}}\right) \tag{2.9.43}$$

$$p_{\mathrm{E,ch,over,act}} = p_{\mathrm{E,ch,over,act}} + p_{\mathrm{E,ch,over,dyno}} \cdot \frac{\Delta t}{t_{\mathrm{E,ch,build-up}}} \tag{2.9.44}$$

For the response time a constant value or the value out of the map is used.

2.9.7.1 Evaluation of the engine torque [2]

$\alpha_{\mathrm{E,th}} = 0 \rightarrow$ Motoring Curve
$\alpha_{\mathrm{E,th}} = 1 \rightarrow$ Full Load Characteristic

$$p_{\mathrm{eff,theo}} = p_{\mathrm{eff,sk}} + \left(p_{\mathrm{eff,vk}} - p_{\mathrm{eff,sk}}\right) \cdot \alpha_{\mathrm{E,th}} \tag{2.9.45}$$

If the requested engine torque comes from the Data Bus as 'Desired Torque,' this value is directly converted into $p_{\mathrm{eff,theo}}$ and then limited by $p_{\mathrm{eff,vk}}$.

2.9.7.2 Response Time [2]

If $\left(\boldsymbol{p_{\mathrm{eff,theo}} > p_{\mathrm{eff,theo,old}} + p_{\mathrm{eff,max}} \cdot \frac{\Delta t}{t_{\mathrm{E,add}}}}\right)$

$$\boldsymbol{p_{\mathrm{eff,theo}} = p_{\mathrm{eff,theo,old}} + p_{\mathrm{eff,max}} \cdot \frac{\Delta t}{t_{\mathrm{E,add}}}} \tag{2.9.46}$$

2.9.8 Temperature Models

In AVL CRUISE, there are three options to determine the actual temperature of the engine:

- Pre-defined temperature characteristic
- Temperature from Data Bus
- AVL temperature model

2.9.8.1 Pre-defined temperature characteristic

Here the actual engine temperature is linear interpolated out of a user-defined characteristic.

2.9.8.2 Temperature from Data Bus

When the engine temperature is calculated in an external component (Black Box, MATLAB®, Flowmaster) or the function component or defined in the general map, it can be transferred into the engine component through the Data Bus input channel 'Temperature External.'

Task and cycle-dependent temperature characteristics can be defined in the Vehicle and the actual temperature values can be made available on the Data Bus. For this option, the switch 'Pre-defined Temperature Curve' has to be activated in the task (Cycle Run and Cruising).

2.9.8.3 AVL Temperature Model

The heat produced by the combustion can be computed by considering the fuel consumption. This heat is distributed among the engine block and exhaust gas by a factor. The heating of the engine can be computed by considering the temperature loss in the radiator. Thus, the engine temperature can be computed.

This technique has two advantages: First, the actual heat flow in the engine is represented. Second, the required data can be measured on the testbed with but little expenditure. No transient maps to be determined in a complex way are required.

For the computation of the engine temperature, the following ideas are used:

- The heat capacity of the injected fuel (fuel consumption of the warm engine plus additional fuel consumption caused by the increasing friction mean pressure) is the input to the engine system (engine + cooling system). To estimate the heat capacity of this system, an equivalent mass of water ($m_{E,eq}$) with the same heat capacity has to be given.
- One part of the fuel energy is given off as work. The rest is divided into two parts: The first part goes to the exhaust gas system ($Z_{E,EE}$), the second part is the input to the equivalent mass.

The heat produced by the combustion will be computed from this formula [2]:

$$P_{\mathrm{E,heat}} = b_{\mathrm{E,h,act}} \cdot \rho_{\mathrm{E,fuel}} \cdot H_{\mathrm{E,fuel}} \tag{2.9.47}$$

The mechanical power take-off [2]:

$$P_{\mathrm{E,act}} = M_{\mathrm{E,act}} \cdot \dot{\varphi}_{\mathrm{E,out}} \tag{2.9.48}$$

The loss power in the exhaust emissions [2]:

$$P_{\mathrm{E,emis}} = Z_{\mathrm{E,EE}} \cdot \left(P_{\mathrm{E,heat}} - P_{\mathrm{E,act}}\right) \tag{2.9.49}$$

The rest energy has to go into the cooling system [2]:

$$P_{\mathrm{E,cool}} = P_{\mathrm{E,heat}} - P_{\mathrm{E,act}} - P_{\mathrm{E,emis}} \tag{2.9.50}$$

- For the equivalent mass a thermal balance is made.

Input is the rest of the fuel energy. Output is the energy lost to the environment by cooling (cooling characteristic: small cooling cycle—only a small loss of heat; large cooling cycle—high loss of heat). With the resulting stored heat in the equivalent mass and the specific heat of the water the temperature of the equivalent mass can be computed.

T_{E} Actual engine temperature
$c_{\mathrm{E,v,cool}}$ Heat capacity [J/K]

With a linear interpolation in the cooling characteristic, the value $c_{\mathrm{E,v,cool}}$ is evaluated.

This value is transformed [2]:

$$\alpha_{\mathrm{A}} = c_{\mathrm{E,v,cool}} \cdot \left(1 + 0.4 \cdot \frac{v_{\mathrm{V,act}}}{83}\right) \tag{2.9.51}$$

And the engine temperature can be calculated [2]:

$$T_{\mathrm{E}} = T_{\mathrm{E}} + \frac{\left(P_{\mathrm{E,cool}} - \alpha_{\mathrm{A}} \cdot \left(T_{\mathrm{E}} - T_{\mathrm{W,air}}\right)\right) \cdot \Delta t_i}{m_{\mathrm{E,eq}} \cdot c_{\mathrm{p,H_2O}}} \tag{2.9.52}$$

where $c_{\mathrm{p,H_2O}} = 4187 \frac{\mathrm{J}}{\mathrm{kg \cdot K}}$

2.9.9 Consumption Models

In AVL CRUISE, the following models and methods can be used for the calculation of the higher fuel consumption while the engine is cold:

- Warm-up Enrichment
- Cold Start Correction
- FC External and FC Coefficient External
- Increasing Friction Mean Pressure
- Increase by Mean Pressure Factor

2.9.9.1 Warm-up Enrichment

Here, the additional fuel consumption during warm-up is interpolated from a user-defined characteristic depending on temperature.

2.9.9.2 Cold Start Correction (for Cycle Run and Cruising)

The actual fuel consumption is multiplied with cold start factor which is defined the in the component vehicle. The factor can be defined for different cycles as a function of time. In the task, the switch 'Cold Start Correction' has to be activated.

2.9.9.3 FC External and FC Coefficient External

FC External
An additional fuel consumption from the Data Bus input channel 'Additional FC (Mass Flow)' is added to the originally determined fuel consumption.

FC Coefficient External
The determined fuel consumption (inclusive additional external FC) is multiplied with the FC coefficient delivered by the Data Bus input channel 'FC Coefficient External.'

2.9.9.4 Increasing Friction Mean Pressure

The characteristic for the friction mean pressure is given by the friction mean pressure at minimum ($p_{E,min}$) and maximum speed ($p_{E,max}$) and a curvature factor ($c_{E,fric,p}$) between them ($c_{E,fric,p} = 1$ means a linear characteristic; refer to Fig. 2.11).

At first, a reference value for the mean friction pressure is calculated [2]:

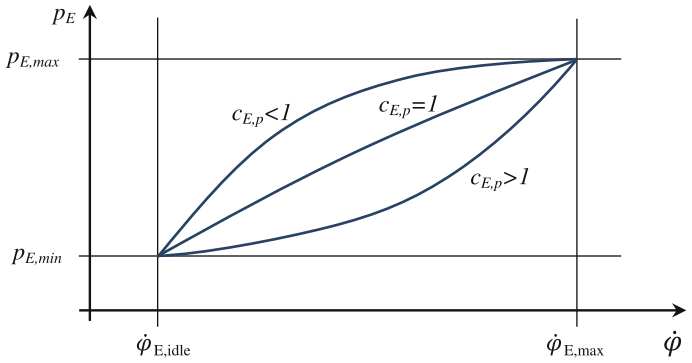


Fig. 2.11 Friction mean pressure [2]

$$f_B = \frac{p_{E,fric,max} - p_{E,fric,min}}{\left(\dot{\varphi}_{E,max}\right)^{c_{E,fric,p}} - \left(\dot{\varphi}_{E,idle}\right)^{c_{E,fric,p}}} \tag{2.9.53}$$

$$f_A = p_{E,fric,min} - f_B \cdot \left(\dot{\varphi}_{E,idle}\right)^{c_{E,fric,p}} \tag{2.9.54}$$

$$p_{E,fric,ref} = f_A + f_B \cdot \left|\dot{\varphi}_{E,out}\right|^{c_{E,fric,p}} \tag{2.9.55}$$

The dependence on the temperature is done via the dynamic oil viscosity. Here, only the oil viscosity at 40 °C ($\eta_{E,40}$) is needed. The oil viscosity at other temperatures is calculated by means of an empirical equation [2]:

$$f_{help} = 159.56 \cdot \ln\left|\frac{\eta_{E,40}}{1.8 \cdot 10^{-4}}\right| \tag{2.9.56}$$

$$\eta(T) = 1.8 \cdot 10^{-4} \cdot e^{\left(\frac{f_{help}}{T-273.15+95}\right)} \cdot e^{\left(\frac{-f_{help}}{887}\right)} \tag{2.9.57}$$

$$\eta_{E,act} = \eta(T_E)\eta_{E,ref} = \eta\left(T_{E,N}\right) \tag{2.9.58}$$

For the conversion of the oil viscosity into the friction mean pressure, the exponent of friction mean pressure ($c_{E,vis,exp}$) is needed. The equation for is as follows:

$$p_{E,fric,add} = p_{E,fric,ref} \cdot \left(\left|\frac{\eta_{E,act}}{\eta_{E,ref}}\right|^{c_{E,fric,exp}} - 1\right) \tag{2.9.59}$$

The friction mean pressure, the Fuel Consumption Maps, and the emission maps are given at the nominal temperature ($T_{E,N}$). For the correction of the fuel consumption the working point in the engine is changed. For this the change in friction, mean pressure between the actual temperature and the nominal temperature is

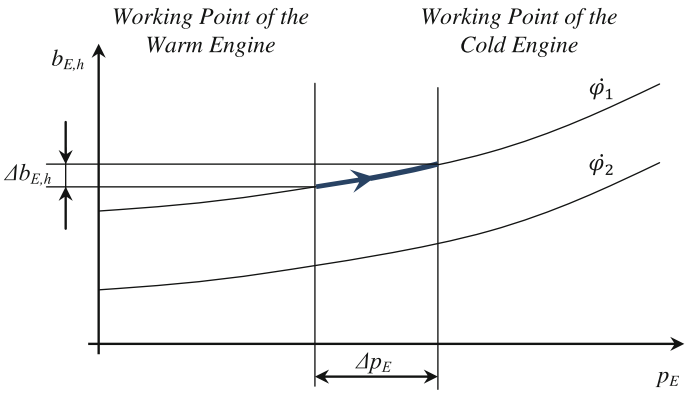


Fig. 2.12 Change of working point in the cold engine [2]

calculated and added in the Fuel Consumption Map. So the working point is changed to a higher (actual temperature is lower than the nominal temperature) or to a lower (actual temperature is higher than the nominal temperature) mean pressure.

With this other working point, the fuel consumption is also increasing or decreasing (Refer to Fig. 2.12).

2.9.9.5 Increase by Mean Pressure Factor

Similar to the consumption increase by increased friction mean pressure the increased friction mean pressure in the cold engine is calculated. In contrast to the other method the mean pressure of the cold engine is divided by the mean pressure of the warm engine. The factor is then applied on the fuel consumption as well as on the emissions.

2.9.9.6 Advanced Friction Model

Introduction

The principal factors influencing a vehicle's fuel consumption can be determined on the basis of this definition of consumption per distance.

They can be categorized as:

1. Contribution factors related to motor (Engine Losses),
2. Drivetrain Losses, and
3. Exterior resistance

There is continuing interest in better understanding the friction losses in internal combustion engines. These adversely affect the maximum work output and fuel

economy characteristics of an engine, directly account for much of the difference in fuel consumption between cold and full-warm engine operation.

The engine losses may be grouped as follows:

1. Mechanical friction,
2. Pumping losses,
3. Exhaust losses, and
4. Heat transferred to the environment, convection in the coolant circuit and radiation in engine compartment.

An accurate friction model must account for engine design variables such as bore, stroke, and number of valves and must consider engine operating conditions such as speed, load, and oil temperature. The friction model must also accurately distribute the friction within the engine, and for this application, be based on generable scalable engine parameters.

The friction model, which best satisfies these criteria is the one developed by Patton et al. [3], PNH. The treatment of the power losses using PNH model is for fully warmed-up engine running conditions. The model brake down the friction losses into component parts associated with the main bearings, the valve train, piston group and auxiliary components. Each friction component is used to define and locate appropriate heat sources for the frictional heating of the lubricating oil flow.

II. Engine Losses: PNH Model

A. Mechanical Friction

1. Crankshaft

The crankshaft means effective pressure can be expressed as follows [2]:

$$\text{fmep} = c_{\text{cb}}\left(\frac{ND_{\text{b}}^3 L_{\text{b}} n_{\text{b}}}{B^2 s n_{\text{c}}}\right) + C_{\text{cs}}\left(\frac{D_{\text{b}}}{B^2 s n_{\text{c}}}\right) + c_{\text{td}}\left(\frac{N^2 D_{\text{b}}^2 n_{\text{b}}}{n_{\text{c}}}\right) \tag{2.9.60}$$

B	Bore	m
S	Stroke	m
D_{b}	Bearing diameter	m
L_{b}	Bearing length	m
n_{b}	No. of bearings	–
n_{c}	No. of cylinders	–
N	Engine rotational Speed	rpm
C_{cb}	Coefficient of the hydrodynamic losses in main bearings	Pa/rpm m
C_{cs}	Coefficient of friction losses in main bearing seals	Pa m^2
C_{td}	Coefficient of friction losses due to viscous dissipation	Pa s^2/m^2 rpm

2. **Piston (Reciprocating) Group**

The friction means effective pressure in the reciprocating group may be calculated using the following equation [2]:

$$mep_{\mathrm{pb}} = c_{\mathrm{pb}}\left(\frac{ND_{\mathrm{b}}^3 L_{\mathrm{b}} n_{\mathrm{b}}}{B^2 S n_{\mathrm{c}}}\right) + C_{\mathrm{ps}}\left(\frac{V_{\mathrm{p}}}{B}\right) + C_{\mathrm{pr}}\left(1 + \frac{10^3}{N}\right)\left(\frac{1}{B^2}\right) C_{\mathrm{o}} \cdot \frac{P_{\mathrm{i}}}{P_{\mathrm{a}}}\left(0.088 r_{\mathrm{c}} + 0.182 r_{\mathrm{c}}^{\left(1.33 - 2.38 \times 10^{-2} V_{\mathrm{p}}\right)}\right) \tag{2.9.61}$$

where:

C_{cb}	Coefficient for connecting rod bearing hydrodynamics	Pa/rpm m
C_{ps}	Coefficient for skirt-cylinder wall hydrodynamics	Pa s
C_{pr}	Coefficient for piston ring-cylinder wall	Pa m^2
C_{o}	Coefficient for gas pressure to ring friction	Pa
V_{p}	Mean piston speed	m/s

3. **Valve Train**

The friction means effective pressure in the valve train is calculated using the following equation [2]:

$$\mathrm{Fmep}_{\mathrm{cv}} = c_{\mathrm{vb}}\left(\frac{Nn_{\mathrm{b}}}{B^2 S n_{\mathrm{c}}}\right) + c_{\mathrm{vo}} + C_{\mathrm{vh}}\left(\frac{L_v^{1.5} N^{0.5} n_{\mathrm{v}}}{B S n_{\mathrm{c}}}\right) + C_{\mathrm{vm}}\left(1 + \frac{10^3}{N}\right)\frac{L_{\mathrm{v}} n_{\mathrm{v}}}{S n_{\mathrm{c}}} + \mathrm{Fmep}_{\mathrm{cam\ follower}} \tag{2.9.62}$$

Flat Cam Follower [2]:

$$\mathrm{Fmep}_{\mathrm{cam\ follower}} = C_{\mathrm{vf}}\left(1 + \frac{10^3}{N}\right)\frac{n_{\mathrm{v}}}{s n_{\mathrm{c}}} \tag{2.9.63}$$

Roller Cam Follower [2]:

$$\mathrm{Fmep}_{\mathrm{cam\ follower}} = C_{\mathrm{vr}}\left(\frac{Nn_{\mathrm{v}}}{s n_{\mathrm{c}}}\right) \tag{2.9.64}$$

where:

C_{vb}	Coefficient for camshaft bearing hydrodynamic	Pa m^3/rpm
C_{vh}	Oscillating hydrodynamic lubrication constant	Pa $m^{0.5}$/$rpm^{0.5}$
C_{vm}	Oscillating mixed lubrication constant	Pa
C_{vo}	Boundary lubrication constant due to the camshaft bearing seals	Pa
L_{v}	Maximum valve lift	m

(continued)

n_v	No. of valves	–
C_{vf}	Flat cam follower constant	Pa m
C_{vr}	Roller cam follower constant	Pa m

Both of the cam followers' constants depend on the valve train configuration.

4. **Auxiliary Losses**
   The following equation can be used to calculate the FMEP due to the auxiliaries [2]:

$$\text{Fmep}_{\text{aux}} = \alpha + \beta N + \gamma N^2 \tag{2.9.65}$$

The constants α, β and γ are used to be 6.23×10^3 Pa, 5.22 Pa/rpm, -1.79×10^{-4} Pa/rpm^2, respectively.

B. **Pumping Losses**
The correlation used by Bohic has been used. That is [2]:

$$\text{Pmep} = 10^5 \frac{\text{Disp}}{0.0025} \cdot \left(0.0785 + 4.02\times10^{-5}\text{N} + 1.06 \times 10^{-8}\text{N}^2 + 4.64 \times 10^{-8}\text{IMEP} + 2.17\times10^{-10}\text{N}\times\text{IMEP}\right) \tag{2.9.66}$$

where: IMEP, Disp are the indicated mean effective pressure and engine displacement, respectively.

III. Engine Losses: Modified PNH Model

The rate at which the engine structure and lubricating oil warm-up influences friction losses over the cycle, because these depend on oil viscosity, which in turn depends upon temperature. The friction power losses drop sharply over the first 50 s of engine warm-up [4], after which the rate of fall is greatly reduced. Such behavior indicates that friction level changes are likely to be influenced by the oil viscosity. The effect of viscosity changes is taken into account by scaling the instantaneous friction loss in proportion to values for fully warmed up [2].

$$\frac{\text{FmepT}_{\text{oil}}}{\text{FmepT}_{\text{oil}} = 90\ ^\circ\text{C}} = \left(\frac{\nu\text{T}_{\text{oil}}}{\nu\text{T}_{\text{oil}} = 90\ ^\circ\text{C}}\right)^{0.24} \tag{2.9.67}$$

IV. Engine Losses: SLM Model

Shayler et al. [5], SLM, compiled and examined the model fits friction teardown data from motored engine tests on 4 cylinder diesel engines. The original purpose of the experimental work was to examine friction losses at low temperatures and low engine speeds in connection with studies of cold start behavior. At low, sub-zero temperature typically between −20 and −30 °C, engine friction take causes a substantial increase in the time taken to complete the start-up process. The focus had been on capturing the characteristics of the experimental data for cold, low speed operating conditions. The bulk of the experimental data was obtained through motoring tests carried out on engines enclosed within a compact cold cell. The test

engine was motored by a DC motor with an in-line torque transducer in the driveline connecting the DC motor and the test engine. Friction teardown was carried out on four engine designs.

A. **Mechanical Friction**

1. **Crankshaft**

Friction Mean Effective Pressure in the crankshaft group is calculated using the following equation [2]:

$$\text{Fmep}_{\text{crankshaft}} = c_{\text{cb}}\left(\frac{N^{0.6}D_{\text{b}}^{3}L_{\text{b}}n_{\text{b}}}{B^{2}Sn_{\text{c}}}\right)\left(\frac{\mu}{\mu_{\text{ref}}}\right)^{n} + C_{\text{cs}}\left(\frac{D_{\text{b}}}{B^{2}Sn_{\text{c}}}\right) \tag{2.9.68}$$

where:

C_{cb}	Coefficient of the hydrodynamic losses in main bearings	Pa/rpm m
C_{cs}	Coefficient of friction losses in main bearing seals	Pa m^2
n	Viscosity index	–
μ	Oil dynamic viscosity at the operating temperature	Pa s
μ_{ref}	Oil dynamic viscosity at fully warm, reference condition	Pa s

2. **Piston (Reciprocating) Group**

Means effective pressure due to the friction in the piston group is expressed as follows [2]:

$$\text{Fmep}_{\text{piston}} = \left(c_{\text{pb}}\left(\frac{N^{0.6}D_{\text{b}}^{3}L_{\text{b}}n_{\text{b}}}{B^{2}Sn_{\text{c}}}\right) + C_{\text{ps}}\left(\frac{V_{\text{p}}^{0.5}}{B}\right) + C_{\text{pr}}\left(\frac{V_{\text{p}}^{0.5}}{B^{2}}\right)\right)\left(\frac{\mu}{\mu_{\text{ref}}}\right)^{n} \tag{2.9.69}$$

where:

C_{pb}	Coefficient for connecting rod bearing hydrodynamics	kPa/$\text{rpm}^{0.6}$ mm
C_{ps}	Coefficient for skirt-cylinder wall hydrodynamics	kPa $\text{mm}^{0.5}\text{s}^{0.5}$
C_{pr}	Coefficient for piston ring-cylinder wall	kPa $\text{mm}^{1.5}\text{s}^{0.5}$
n	Viscocity index (=0.4)	–

3. **Valve Train**

Means effective pressure due to the friction in the piston group is expressed as follows [2]:

$$\begin{aligned}\text{Fmep}_{\text{valvetrain}} &= c_{\text{vb}}\left(\frac{N^{0.6}n_{\text{b}}}{B^{2}Sn_{\text{c}}}\right)\left(\frac{\mu}{\mu_{\text{ref}}}\right)^{n} \\ &+ C_{\text{vs}} + C_{\text{vh}}\left(\frac{L_{\text{v}}^{1.5}N^{0.5}n_{\text{v}}}{BSn_{\text{c}}}\right)\left(\frac{\mu}{\mu_{\text{ref}}}\right)^{n} + C_{\text{vm}}\left(2 + \frac{10}{5+\mu N}\right)\frac{L_{\text{v}}n_{\text{v}}}{Sn_{\text{c}}} \\ &+ \text{fmep}_{\text{cam/follower}}\end{aligned} \tag{2.9.70}$$

Flat cam follower [2]:

$$\text{Fmep}_{\text{cam follower}} = C_{\text{vf}}\left(2 + \frac{10}{5 + \mu N}\right)\frac{n_{\text{v}}}{Sn_{\text{c}}} \tag{2.9.71}$$

Roller cam follower [2]:

$$\text{Fmep}_{\text{cam follower}} = C_{\text{vr}}\left(\frac{Nn_{\text{v}}}{Sn_{\text{c}}}\right) \tag{2.9.72}$$

where:

C_{vb}	Coefficient for camshaft bearing hydrodynamic	kPa mm^3/rpm$^{0.6}$
C_{vh}	Oscillating hydrodynamic lubrication constant	Pa mm$^{0.5}$/rpm$^{0.5}$
C_{vm}	Oscillating mixed lubrication constant	Pa
C_{vs}	Boundary lubrication constant due to the camshaft bearing seals	Pa
C_{vf}	Flat cam follower constant	Pa m
C_{vr}	Roller cam follower constant	Pa m
n	Viscosity index	–

4. **Auxiliary Losses** [2]

$$\text{Fmep}_{\text{aux}} = \alpha + \left(\beta N + \gamma N^2\right)\left(\frac{\mu}{\mu_{\text{ref}}}\right)^{\text{n}} \tag{2.9.73}$$

For oil pump, the constants α, β, γ & viscosity index (n) are: 1.28 kPa, 7.9×10^{-3} kPa mm^3/rpm, -8.4×10^{-7} kPa mm^3/rpm^2, 0.3 (viscosity index), respectively. For water pump α, β, γ & viscosity index (n) 0.13 kPa, 2×10^{-3} kPa mm^3/rpm, 3×10^{-7} kPa mm^3/rpm^2, 0.7, respectively. They are: 1.72 kPa, 6.9×10^{-4} kPa mm^3/rpm, 1.2×10^{-7} kPa mm^3/rpm^2, 0.5, respectively for the oil pump.

5. **Pumping Losses**
   The model was developed for motored engines. Therefore, the pumping losses are zero.

2.9.9.7 Fuel Consumption

The fuel consumption is linearly interpolated for the engine speed $\dot{\varphi}_{\text{E,out}}$ and the mean effective pressure $p_{\text{eff,act}}$ out of the fuel consumption map $b_{\text{E,h}}$ $\dot{\varphi}_{\text{E,out}}$, p_{E}.

For $\left(\dot{\varphi}_{\text{E,out}} < \dot{\varphi}_{\text{E,idle}}\right)$ and $\alpha_{\text{th}} < 0$, the fuel consumption can optionally be taken out of the overall map, out of the detailed map, or can be the fixed idle consumption.

2.9.10 Fuel Shut-Off

The fuel shut-off is used to cut off the fuel injection while thrust operation. This is used in modern cars to decrease the fuel consumption

$z_{E,SA}$	Switch for Fuel Shut-Off (Yes/No)	–

For the fuel cut-off, two speeds are necessary to create a hysteresis so that the fuel shut-off is not always activated and deactivated in too short times.

$\dot{\varphi}_{E,SA,low}$	Lower Speed Border for Fuel Shut-Off	rpm

This speed is the lowest speed the shut-off can work on. If the engine speed falls below this lower speed, the fuel shut-off is deactivated.

$\dot{\varphi}_{E,SA,high}$	Upper Speed Border for Fuel Shut-Off	rpm

This speed has to be reached once that the fuel shut-off can be activated.

$\dot{\varphi}_{E,SA,low,rel}$	Speed Difference above Idle Speed for Lower Speed Limit	rpm
$\dot{\varphi}_{E,SA,high,rel}$	Speed Difference above Idle Speed for Upper Speed Limit	rpm

If 'Relative Speed Differences' are chosen, the upper and lower speed borders are calculated with these values relative to the actual idle speed.

$b_{E,SA}$	Residual Fuel Consumption	l/h

The residual fuel consumption is the fuel consumption while the fuel shut-off is active.

This is, for example, needed if you have an additional heater.

$z_{E,SA,fc}$	Consumption Increase after Deactivation (linear/sharp rise)	–

The button for **Consumption Increase after Deactivation** is to change the way the fuel consumption is increasing after the fuel shut-off is deactivated (refer to Figs. 2.13 and 2.14).

(a) for $\left(\dot{\varphi}_{E,act} \leq \dot{\varphi}_{E,SA,low}\right)$ and $Z_{E,SA,fc}$ = activated [2]:

$$b_{E,act} = b_{E,idle} - \frac{b_{E,idle} - b_{E,SA}}{\dot{\varphi}_{E,SA,low} - \dot{\varphi}_{E,idle}} \cdot \left(\dot{\varphi}_{E,act} - \dot{\varphi}_{E,idle}\right) \tag{2.9.74}$$

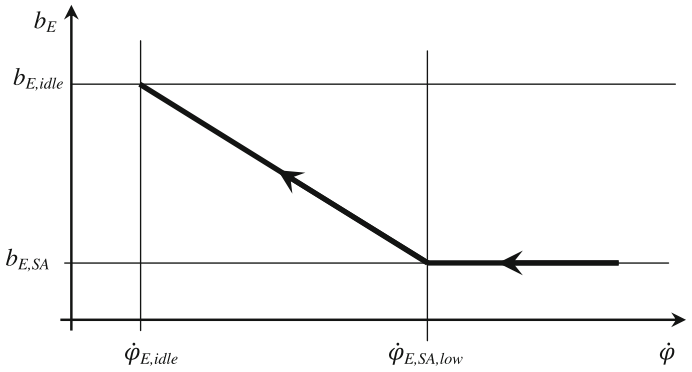


Fig. 2.13 Consumption increase after deactivation *linear* [2]

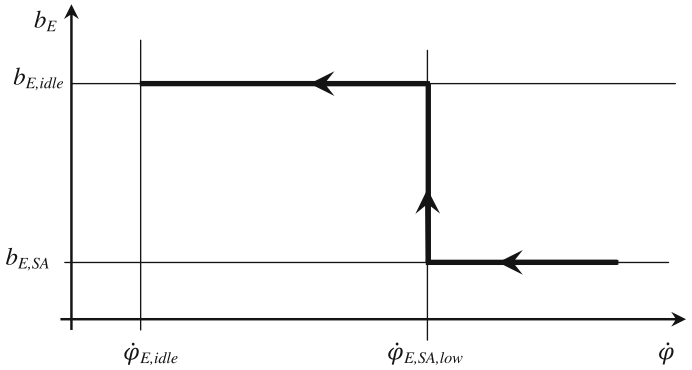


Fig. 2.14 Consumption increase after deactivation sharp rise [2]

(b) for $\left(\dot{\varphi}_{\mathrm{E,act}} > \dot{\varphi}_{\mathrm{E,SA,low}}\right)$ [2]:

$$b_{\mathrm{E,act}} = b_{\mathrm{E,SA}} \tag{2.9.75}$$

2.9.10.1 Emissions

At first the factor of fuel consumption is evaluated. It is the relation between the actual and the map consumption [2]:

$$f_{\mathrm{fuel}} = \frac{b_{\mathrm{E,act}}}{b_{\mathrm{E,h}}} \tag{2.9.76}$$

The emissions are linear interpolated out of the maps for $\dot{\varphi}_{\mathrm{E,act}}$ and $P_{\mathrm{E,act}}$.

This values out of the map have to be transformed with f_{fuel} [2]:

$$e_{\text{E,xx,act}} = e_{\text{E,xx}} \cdot f_{\text{fuel}} \tag{2.9.77}$$

2.9.10.2 Start Enrichment

Here, the additional fuel consumption after starting the engine is interpolated out of a user-defined characteristic.

2.9.10.3 Acceleration Enrichment

Here, the additional fuel consumption while stepping on the acceleration pedal is interpolated out of a user-defined characteristic.

2.9.10.4 Starter Current

The charge of battery charge caused by the engine starter is calculated [2]:

$$Q_{\text{E,Q}} = Q_{\text{E,Q}} - \frac{0.5 \cdot \left(I_{\text{E,start}}(t_{i-1}) + I_{\text{E,start}}(t_{i+1})\right)}{\left(I_{\text{E,start}}(t_i) - I_{\text{E,start}}(t_{i-2})\right)} \tag{2.9.78}$$

2.10 Generator (L)

The generator (alternator) must provide the vehicle electrical system with a sufficient supply of current under all operating conditions in order to ensure that the State of Charge (SOC) in the engine storage device (battery) is consistently maintained at an adequate level. The object is to achieve balanced charging, i.e., the curves for performance and speed–frequency response must be selected to ensure that the amount of current generated by the alternator under actual operating conditions is at least equal to the consumption of all electrical equipment within the same period [1].

Automotive alternators are designed to supply charge voltages of 14 V (with 28 V for heavy utility vehicles) in order to maintain an adequate charge in 12 V (or 24 V) batteries.

The alternator produces alternating current. The vehicle's electrical system, on the other hand, requires direct current to recharge the battery and operate the electrical equipment; it is thus direct current that must ultimately be supplied to the electrical system. For this case a rectifier must be provided to convert the alternator's three-phase alternating current into DC.

This arrangement also provides the battery from discharging when the vehicle is stationary. In the input data for the component generator the already into direct

current converted characteristics have to be given. The characteristics used here are measured behind the rectifier [1].

In the component generator a simple regulator is integrated. The regulator works in that way that a threshold voltage has to be defined. If the voltage of the onboard network is below this threshold the generator is activated.

The generator will be separated from the network if the voltage of the onboard network reaches the threshold [1].

The current delivered by the generator results from a map dependent on the speed and the mains voltage. By considering the internal resistance, the instantaneous current consumption helps to acquire the torque absorbed by the generator with the corresponding moments of loss [1].

2.10.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection button Definition
Efficiency Map
Torque and Efficiency Characteristic
The description of the losses in the generator is done by the efficiency map.

Selection button Definition
Efficiency Map
Torque and Efficiency Characteristic
The description of the losses in the generator is done by a speed dependent torque loss (mechanical losses) and a current dependent efficiency (electrical losses).

2.10.2 User-Defined Variables

$U_{G,nom}$	Nominal Voltage	V

The nominal voltage is the threshold voltage for the regulator of the generator. If the voltage in the onboard network is below this threshold the generator is activated. If the voltage is above the threshold the generator is deactivated.

$R_{G,reg,equ}$	Equivalent Resistance Regulator	Ohm

The equivalent resistance regulator defines the gradient of the regulator voltage (see Fig. 2.15).

θ_L	Inertia Moment of the generator	kg m^2

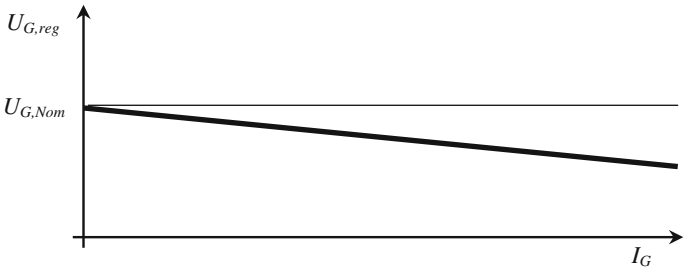


Fig. 2.15 Regulator voltage [2]

Idle Voltage

$R_{G,equ}$	Equivalent Resistance without Regulator	Ohm
The equivalent resistance without regulator defines the gradient of the idle voltage.		
$U_{G,idle}(\dot{\varphi}_{L,gen})$	Idle Voltage as a function of the generator speed	V

The idle voltage is the voltage the generator is producing without an electrical consumer, means that there is no flow of current. This idle voltage is a function of the speed.

Efficiency Map

$\eta_{L,idle}(\dot{\varphi}_L, I_L)$	Efficiency Map	–

The efficiency map describes all losses of the generator (mechanical and electrical). It depends on speed and current.

Torque Loss

$\boldsymbol{M}_{\mathbf{L,pd,gen}}\left(\dot{\boldsymbol{\varphi}}_{\mathbf{L,gen}}\right)$	Torque Loss of the generator as a function of the generator speed	Nm

The moment of loss is the mechanical loss in the generator due to friction at the roller bearings and at the collector ring, aerodynamic friction at the fan, and, above all, the power required to run the fan itself, which increases dramatically at higher speeds.

Together with the torque that is transferred into electrical energy the moment of loss builds the absorbed torque of the whole generator. The moment of loss depends on the generator speed.

Efficiency

$\eta_L(I_L)$	Efficiency as a function of current	–

The efficiency is used to consider the copper and the iron losses. The copper losses are produced by resistance in the rotor and stator windings. Their extent is proportional to the power-to-weight ratio, i.e., the ratio of generated electrical power to the mass of the effective components.

The iron losses result from the hysteresis and eddy currents produced by the alternating magnetic fields in the iron in the stator and rotor. This efficiency is a function of the delivered current.

Maximum Current

$\boldsymbol{I}_{\mathbf{L,max}}\left(\dot{\boldsymbol{\varphi}}_{\mathbf{L,gen}}\right)$	Maximum Generator Current as a function of the generator speed	A

The maximum generator current is the maximum current the generator can deliver. The characteristic depends on the kind of generator (AC, DC).

2.10.3 Input and Output Variables

2.10.3.1 Mechanical Connections

$\dot{\varphi}_{\mathrm{L,in}}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{\mathrm{L,in}}$	Angular acceleration on the drive side	rad/s^2
$M_{\mathrm{L,in}}$	Torque on the drive side	Nm

2.10.3.2 Electrical Connections

$U_{\mathrm{L,net}}$	Actual net voltage	V
I_{L}	Instantaneous generator current	A

2.10.3.3 Data Input

Z_{L}	Switch	–

2.10.3.4 Data Output

$U_{\mathrm{L,net}}$	Net Voltage	V
I_{L}	Current	A
$\dot{\varphi}_{\mathrm{L,in}}$	Speed	rad/s

(continued)

$M_{L,in}$	Generator Torque	Nm
$P_{L,el}$	Electric Power	W
$P_{L,mech}$	Mechanical Power	W
$P_{L,loss}$	Power Loss	W

2.10.4 Computation Variables

$I_{L,max,act}$	Maximum generator current	A
$U_{L,max,act}$	Maximum generator voltage	V
$\dot{\varphi}_{L,cont}$	Generator speed at nominal voltage	rad/s
$I_{L,max,cont}$	Generator current at nominal voltage	A
$U_{L,max,cont}$	Generator Voltage at nominal voltage	V
$C_{L,cont}$	Controller Coefficient	–
$U_{L,switch}$	Voltage for current switching	V

2.10.5 Equation System

2.10.5.1 Charge Controlling

(a) **For the generator current conditions**
The maximum values of the generator current and voltage $I_{L,max,act}$, $U_{L,max,act}$ for a given angular velocity is evaluated out of the maps $U_{L,idle}\left(\dot{\varphi}_{L,gen}\right)$ and $I_{L,max}\left(\dot{\varphi}_{L,gen}\right)$
The minimum voltage is determined be the equation [2]:

$$U_{L,min,act} = U_{L,max,act} - \sqrt{\frac{I_{L,max,act}}{R_{G,equ}}} \tag{2.10.1}$$

(b) **For the controller voltage conditions**
The controller current and voltage $I_{L,max,cont}$, $U_{L,max,cont}$ for a given angular velocity $\dot{\varphi}_{L,cont}$ is evaluated out of the maps $U_{L,idle}\left(\dot{\varphi}_{L,cont}\right)$ and $I_{L,max}\left(\dot{\varphi}_{L,cont}\right)$
The controller factor is defined as function of the controller current [2]:

$$C_{L,cont} = -R_{G,equ} \cdot \frac{1}{I_{L,max,cont}} \tag{2.10.2}$$

The minimum voltage fixed by the controller [2]:

$$U_{\mathrm{L,min,cont}} = U_{\mathrm{L,max,cont}} + C_{\mathrm{L,cont}} \cdot I_{\mathrm{c,max,act}} \tag{2.10.3}$$

Now the program selects between three conditions:

(a) For the generator area higher than the controller minimum voltage:
$U_{\mathrm{L,min,cont}} \leq U_{\mathrm{L,min,act}} \rightarrow$ Controller Charatcteristic
(b) For generator voltage lower than the maximum controller voltage:
$U_{\mathrm{L,max,cont}} \leq U_{\mathrm{L,max,act}} \rightarrow$ Generator Charatcteristic
(c) For the area between: $\rightarrow$ **Mixed Characteristic**

2.10.5.2 Controller Characteristic

The current flow depends on the net and the controller minimum and maximum voltages as well as the controller factor [2]:

$$I_L = -\frac{\left(U_{L,net} - U_{L,\mathrm{min},cont}\right) \cdot \left[1 - \left(U_{L,net} - U_{L,\mathrm{max},cont}\right)\right]}{C_{L,cont} \cdot \left(U_{L,net} - U_{L,\mathrm{max},cont}\right)} \tag{2.10.4}$$

2.10.5.3 Generator Characteristic

In the Generator Characteristic, the current flow is fixed by the net and the controller minimum and maximum voltages as well as the maximum available generator current [2]:

$$I_L = -I_{\mathrm{L,max,act}} - R_{\mathrm{G,equ}} \cdot \left(U_{\mathrm{L,net}} - U_{\mathrm{L,max,act}} + \sqrt{\frac{I_{\mathrm{L,max,act}}}{R_{\mathrm{G,equ}}}}\right)^2 \cdot \left(U_{\mathrm{L,net}} - U_{\mathrm{L,min,act}}\right) \cdot \left[1 - \left(U_{\mathrm{L,net}} - U_{\mathrm{L,max,act}}\right)\right] \tag{2.10.5}$$

2.10.5.4 Mixed Characteristic

In the Mixed Characteristic, the conditions are changing between Generator Characteristic and Controller Characteristic. The switch voltage determines the actual used characteristic [2]:

$$U_{\mathrm{L,switch}} = -\frac{b}{2 \cdot a} + \sqrt{\frac{b^2 - 4 \cdot a \cdot c}{2 \cdot a}} \tag{2.10.6}$$

$$a = -R_{\mathrm{G,equ}} \tag{2.10.7}$$

$$b = -2 \cdot \left(-U_{\mathrm{L,max,act}} + \sqrt{\frac{I_{\mathrm{L,max,act}}}{R_{\mathrm{G,equ}}}} \right) \cdot R_{\mathrm{G,equ}} - \frac{1}{C_{\mathrm{L,cont}}} \tag{2.10.8}$$

$$c = I_{\mathrm{C,max,act}} \cdot R_{\mathrm{G,equ}} \cdot \left(-U_{\mathrm{L,max,act}} + \sqrt{\frac{I_{\mathrm{L,max,act}}}{R_{\mathrm{G,equ}}}} \right)^2 + \frac{U_{\mathrm{L,max,cont}}}{C_{\mathrm{L,cont}}} \tag{2.10.9}$$

If the net voltage is lower than the switch voltage:
$U_{\mathrm{L,net}} < U_{\mathrm{L,switch}} \rightarrow$ Generator Characteristic
else
$U_{\mathrm{L,net}} \geq U_{\mathrm{L,switch}} \rightarrow$ Controller Characteristic

Efficiency

The generator efficiency $\eta_{\mathrm{L,act}}$ for the actual loading conditions is evaluated out of the efficiency curve for the actual generator current I_{L}.

Torque

(a) **Evaluation with loss torque**
For the torque calculation, the loss moment and the working moment have to be added. The loss moment $M_{\mathrm{L,pd,act}}$ is interpolated out of the loss function.
Thus, we can write the equation for the whole generator torque [2]:

$$M_{\mathrm{L,in}} = M_{\mathrm{L,pt,act}} - \frac{I_{\mathrm{L}} \cdot U_{\mathrm{L,net}}}{Z_{\mathrm{L}} \cdot \dot{\varphi}_{\mathrm{L,in}}} \tag{2.10.10}$$

(b) **Evaluation with efficiency value**
The overall efficiency value $\eta_{\mathrm{L,act}}$ is evaluated out of the map for the actual current flow and the generator speed.
Thus, we can write the equation for the whole generator torque [2]:

$$M_{\mathrm{L,in}} = -\frac{1}{\eta_{\mathrm{L,act}}} \cdot \frac{I_{\mathrm{L}} \cdot U_{\mathrm{L,net}}}{\eta_{\mathrm{L,el}} \cdot \dot{\varphi}_{\mathrm{L,in}}} \tag{2.10.11}$$

2.11 Electrical Consumer (X)

Electric consumers are represented as ohmic resistors in the onboard network. They represent an electric current loss. The number of the resistors that can be defined is user-dependent. The resistors can be fixed by a constant value or by means of

characteristic curves. It is possible to define resistors as a function of any external input value. It is also possible to define an external switch that switches on and off the resistor depending on the exceeding of an external value [1].

2.11.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Definition
Resistance
Current (Power)
The Resistance is defined depending on the value of the Data Bus input 'Set Value X'.

Selection Button Definition
Resistance
Current (Power)
In this case, the Current or Power has to be defined depending on the values of the Data Bus inputs 'Set Value X' and 'Set Value Y'.

2.11.2 User-Defined Variables

$U_{x,nom}$	Nominal Voltage	V

The nominal voltage is the definition of the voltage in the onboard network.

$U_{x,border}$	Threshold Value	–
$Z_{x,dir}$	Direction (positive/negative)	–
$Z_{x,ref}$	Reference (absolute/relative)	–
$Z_{x,exceed}$	Exceeding of Value Range (admissible/inadmissible)	–

Resistance Curve
The Resistance Curve has to be defined if the selection button 'Definition' is set to *Resistance*.

$R_x(\text{setValue}_X)$	Resistance as function of Set Value X	Ω

As described before the electrical consumer can be described as resistance depending on any input value. In addition it is possible to define a switch for the resistor. To do this the electrical consumer has to be connected to the Data Bus. In this Data Bus there are two input values:
Set value: This is the value the resistance depends on.

Switch: This is used to switch the resistor on and off depending on exceeding a definable value of the switch. For this connected switch you can define a threshold (Ux, border) which is the border for the on and off switching.

For on and off switching there are different possibilities:

Direction (positive/negative): Positive means that the switch is turned on when the input of the switch is above the threshold value and it is turned off when the input of the switch is below the threshold value. If negative is chosen it is vice versa.

Reference (absolute/relative): The resistance is defined dependent on an input value. If absolute is chosen the resistance is switched on and off when the switch is turned on and off. If relative is chosen the resistance starts every time the switch is turned on at zero.

Exceeding of value range (*admissible/inadmissible*): Sometimes it can occur that the switch is longer open than the resistance is defined or that the set value is outside the defined range (e.g. the resistance is defined as a function of the engine speed with a maximum of 6000 rpm and the engine speed reaches 6500 rpm, i.e., that the resistance is outside the defined value range. If the exceeding of value range is inadmissible the switch will be turned off when the defined border is reached. If exceeding of value range is admissible the resistance will be extrapolated to get data for the resistance.

Current (Power) Map

The Current (Power) map has to be defined if the selection button 'Definition' is set to *Current (Power)*.

$I_x(\text{setValue}_X, \text{setValue}_Y)$ or $P_x(\text{setValue}_X, \text{setValue}_Y)$	Current or Power as function of Set Value X and Set Value Y	A or W

The Current or Power is defined depending on the values of the Data Bus Inputs 'Set Value X' and 'Set Value Y'.

Additionally, the map interpolation mode can be selected between 'Continuous' and 'Steplike'. For further description of these modes, please refer to the description of component 'Map'.

2.11.3 Input and Output Variables

2.11.3.1 Electrical Connection

$U_{X,net}$	Net voltage	V
I_X	Current absorbed by the consumer	A

2.11.3.2 Data Input

$S_{X,act}$	Switch	–
$Z_{X,act}$	Set Value X	–
$Z_{Y,act}$	Set Value Y	–

2.11.3.3 Data Output

I_x	Current	A
$U_{X,net}$	Net voltage	V
P_x	Power	W

2.11.4 Computation Variables

$R_{X,act}$	Actual internal resistance	Ω

2.11.5 Equation System

The electrical consumer is switched on or off dependent on the switch and the regulation value.

The actual inner resistance $R_{X,act}$ is evaluated out of the map with consideration of the current switch position.

With this, the instantaneous current can be calculated [2]:

$$I_X = \frac{U_{X,net}}{R_{X,act}} \tag{2.11.1}$$

2.12 Electric Motor (J)

The electric motor can be used for electrically driven vehicles, cars with hybrid drive or to operate auxiliaries such as a fan or an oil pump.

The electric motor is defined by means of characteristic curves. Therefore, different motor type models can be constructed [1].

2.12.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Definition
Efficiency
Efficiency Map
Load-dependent Efficiency Maps
Current Map
The efficiency is defined as a constant value. In addition to the torque map, the efficiency-current curves (idle current map, starting current map) have to be given.

Selection Button Definition
Efficiency
Efficiency Map
Load-dependent Efficiency Maps
Current Map
Here the efficiency map has to be defined. Then the current–voltage characteristic is calculated with the efficiency map and the torque-speed map.

Selection Button Definition
Efficiency
Efficiency Map
Load-dependent Efficiency Maps
Current Map
In addition to the torque map and the efficiency–current curves, there can be up to 5 load-dependent efficiency maps defined.
The efficiency value of the actual voltage is interpolated from this data.

Selection Button Definition
Efficiency
Efficiency Map
Load-dependent Efficiency Maps
Current Map
The Motor Characteristic is defined by the torque map and the current–voltage map.

5. **Switches: Load-Dependent Efficiency Map $\mathbf{U}_1$, …, $\mathbf{U}_5$**
If the selection button **Definition** is set to *Load-dependent Efficiency Maps,* up to 5 efficiency maps can be defined for up to 5 voltage levels.

2.12.2 User-Defined Variables

θ_J	Inertia Moment of the Electric Motor	kg m^2

$\dot{\boldsymbol{\varphi}}_{\mathbf{J,min}}$	Minimum Speed	rad/s

The minimum speed is the minimum angular velocity the electric motor can run at.

$\dot{\boldsymbol{\varphi}}_{\mathbf{J,max}}$	Maximum Speed	rad/s

The maximum speed is the maximum angular velocity the electric motor can run at.

$U_{\mathrm{J,nom}}$	Nominal Voltage	V

The nominal voltage is defined for every electric motor. Normally it should be the same as in the whole onboard network.

η_{J}	Efficiency	%

This input can only be provided if the selection button **Definition** is set to *Efficiency*.

$\boldsymbol{M}_{\mathbf{J}}(\dot{\boldsymbol{\varphi}}_{\mathbf{J,out}}, \boldsymbol{U}_{\mathbf{J}})$	Torque–Voltage Map of Motor	Nm

Map of the output torque dependent on the speed and the voltage.

$\boldsymbol{I}_{\mathbf{J}}(\dot{\boldsymbol{\varphi}}_{\mathbf{J,out}}, \boldsymbol{U}_{\mathbf{J}})$	Current–Voltage Map of Motor	A

Map of the absorbed current dependent on the speed and the voltage.

$\eta_{\mathbf{J}}(\dot{\boldsymbol{\varphi}}_{\mathbf{J,out}}, \boldsymbol{U}_{\mathbf{J}})$	Efficiency Map	–

Efficiency map is dependent on the speed and the voltage. It has to be defined when selected in the property window. In addition the starting current value has to be given.

$\eta_{\boldsymbol{J,i}}(\dot{\boldsymbol{\varphi}}_{\mathbf{J,out,i}}, \boldsymbol{P}_{\mathbf{J,i}})$	Load-dependent Efficiency Maps i = 1, …,5	–

For each voltage level selected by the *Load-dependent Efficiency Maps* switches, efficiency map depending on the speed and the electrical power can be defined.

$\boldsymbol{I}_{\mathbf{J}}(\dot{\boldsymbol{\varphi}}_{\mathbf{J,out}})$	Idle Current Curve	A

Curve of the absorbed current dependent on the idle speed.

$\boldsymbol{I}_{\mathbf{J,A}}(\boldsymbol{\theta}_{\mathbf{J,out}})$	Starting Current Curve	A

Curve of the absorbed current dependent on the starting speed.

The last 2 curves must be defined if the selection button **Definition** is set to *Efficiency* or *Load-dependent Efficiency Maps.*

2.12.3 Input and Output Variables

2.12.3.1 Mechanical Connections

$\dot{\boldsymbol{\varphi}}_{\mathbf{J,out}}$	Angular velocity of the motor	rad/s
$\ddot{\boldsymbol{\varphi}}_{\mathbf{J,out}}$	Angular acceleration of the motor	rad/s^2
$M_{\mathbf{J,out}}$	Instantaneous motor torque	Nm

2.12.3.2 Electrical Connections

$U_{\mathrm{J,net}}$	Net Voltage	V
I_{J}	Absorbed motor current	A

2.12.3.3 Data Input

α_{J}	Load Signal	–
z_{J}	Switch	–

2.12.3.4 Data Output

$K_{\mathrm{J,act}}$	Operation Control	–
$U_{\mathrm{J,net}}$	Net Voltage	V
$\dot{\varphi}_{\mathrm{J,out}}$	Speed	rad/s
$M_{\mathrm{J,out}}$	Electric Motor Torque	Nm
Q_{J}	Energy Consumption	As
I_{J}	Current	A
P_{J}	Mechanical Power	W
$P_{\mathrm{J,loss}}$	Power Loss	W

2.12.4 Computation Variables

$M_{J,act}$	Actual motor moment	Nm
$I_{J,act}$	Actual motor current	A
$\eta_{J,act}$	Actual efficiency value of the motor	–
$I_{J,A}$	Starting Current of the motor	A
$P_{J,el,act}$	Actual electrical power of the motor	W
$P_{J,mech,act}$	Actual mechanical power of the motor	W
$U_{J,act}$	Actual voltage of the motor	V
α_J	Load control signal	–

2.12.5 Equation System

2.12.5.1 Mechanical Part

For the actual angular velocity n_{act} and the actual voltage the actual values of M_J are calculated:

n, n_{act}... (actual) speed of the motor [2]:

$$M_{J,act} = M(n_{act}, U_{act}) \cdot \alpha_J \tag{2.12.1}$$

For the actual angular velocity n_{act} and the actual net voltage, the actual value of the mechanical power is determined from the torque map M (n_{act}, $U_{J,act}$) [2]:

$$P_{J,mech,act} = M_{J,act} \cdot n_{act} \tag{2.12.2}$$

2.12.5.2 Electrical Part

Current–Voltage Map

Calculation of the actual current by the current–voltage map [2]:

$$I_{J,act} = I\left(n_{act}, U_{J,net}\right).abs(\alpha_J) \tag{2.12.3}$$

Constant Efficiency Value

Calculation by efficiency value, idle current map, and starting current map. Actual electrical power [2]:

$$P_{\mathrm{J,el,act}} = \frac{P_{\mathrm{J,mech,act}}}{\eta_{\mathrm{J}}} \quad \mathrm{n} \neq 0, \quad \mathrm{M} \neq 0 \tag{2.12.4}$$

Actual current of the motor [2]:

$$I_{\mathrm{J,act}} = \frac{P_{\mathrm{J,el,act}}}{U_{\mathrm{J,act}}}. \tag{2.12.5}$$

Special cases:
$n = 0$, $M = 0 \rightarrow I_{\mathrm{act}} = 0$.
$n \neq 0$, $M = 0 \rightarrow$ by the idle current curve: $I_{\mathrm{J,act}} = I(n_{\mathrm{act}})$.
$n = 0$, $M \neq 0 \rightarrow$ by the starting current curve: $I_{\mathrm{J,act}} = I(M_{\mathrm{J,act}})$.

Efficiency Map

Calculation of the actual power and the actual current by the efficiency map and the starting current [2]:

$$P_{\mathrm{J,el,act}} = \frac{P_{\mathrm{J,mech,act}}}{\eta_{\mathrm{J,act}}} \tag{2.12.6}$$

with $\eta_{\mathrm{J,act}} = \eta(n_{\mathrm{act}}, U_{\mathrm{act}})$ with $n \neq 0$ [2]:

$$I_{\mathrm{J,act}} = \frac{P_{\mathrm{J,el,ct}}}{U_{\mathrm{J,act}}} \tag{2.12.7}$$

Special case [2]:

$$n = 0 \rightarrow I_{\mathrm{J,act}} = I_{\mathrm{J,A}}. \tag{2.12.8}$$

Load-dependent efficiency maps

There are maps for certain load levels.
$\eta = f\,(n, P_{\mathrm{J,mech}})$, each $\mathrm{U}_{1,\ \ldots,}\mathrm{U}_5$ can be optionally defined.
Determination of the electrical power [2]:

$$P_{\mathrm{J,el,act}} = \frac{P_{\mathrm{J,mech,ct}}}{\eta_{\mathrm{J,act}}} \tag{2.12.9}$$

whereas $\eta_{\mathrm{J,act}}$ is calculated as follows:
For those (two) voltage levels with $U_{\mathrm{j}} \leq U_{\mathrm{J,act}} \leq U_{\mathrm{k}}$ the $\eta_{\mathrm{j,act}}$ and $\eta_{\mathrm{k,act}}$ act are calculated.

These values are used for the interpolation of $\eta_{\mathrm{J,act}}$.
The current is defined by [2]:

$$I_{\mathrm{J,act}} = \frac{P_{\mathrm{J,el,act}}}{U_{\mathrm{J,act}}} \tag{2.12.10}$$

Special cases:
$n = 0$, $M = 0 \rightarrow I_{\mathrm{J,act}} = 0$.
$n = 0$, $M \neq 0 \rightarrow$ by the starting current curve: $I_{\mathrm{J,act}} = I(M_{\mathrm{J,act}})$.
$n \neq 0$, $M = 0 \rightarrow$ by the idle current curve: $I_{\mathrm{J,act}} = I(n_{\mathrm{act}})$.

Definitions of Idle and Starting

Minimal angular velocity $\dot{\varphi}_{\min}$ maximal angular velocity $\dot{\varphi}_{\max}$... are given by the user; Minimal torque $M_{\min}$, maximal torque $M_{\max}$ … are determined by the torque map $M_{\mathrm{J}}\left(\dot{\varphi}_{\mathrm{J,out}}, U_{\mathrm{J}}\right)$

If the actual values of angular velocity/torque are beyond their 1 %-limit of their maximum values, the engine is in starting/idle status.

Starting limit $\dot{\varphi}_0 = \dot{\varphi}_{\max} \cdot 0.01$

When $\dot{\varphi}_{\mathrm{act}} = \dot{\varphi}_0$ we consider the motor to be in standstill, and the calculation uses the starting current curve.

Idle limit $M_0 = M_{\max} \cdot 0.01$

When $M_{\mathrm{act}} < M_0$, we consider the motor to be in idle status, and the calculation uses the idle current curve.

2.13 Electric Machine (EM)

The Electric Machine component can be used either as an electric motor or as a generator. There are separate Characteristic Maps for each mode. With this component and together with the components battery H and supercapacitor, the user can simulate hybrid systems.

The model of the electric machine contains two components, the inverter and the electric motor. For this kind of model a Characteristic Map for the efficiency is used to calculate the loss of power [1].

The thermal model takes the warm up of the electric machine into account regarding the occurring losses. The warm up of the environment, respectively, the cooling system due to the electric machine is not considered in the electric machine component.

The actual temperature of the semiconductor elements in the inverter must not (not even at starting time or at transient load cycle) exceed the upper limit, since the consequence would be the destruction of the inverter [1].

The maximal power should be restricted to avoid a exceeding of the given limit for the temperature due to the occurring losses. Therefore, the permissible losses are

dependent on the actual temperature of the motor and the maximal moment of inertia is determined according to these values [1].

2.13.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Losses
Efficiency
Power Loss
The efficiency has to be defined depending on speed and power (or torque).

Selection Button Losses
Efficiency
Power Loss
In this case, the power loss has to be defined depending on speed and power (or torque).

Selection Button Temperature
Calculated
From Data Bus
The machine temperature is calculated by the component using a special thermal model. **Selection button Temperature**
Calculated
From Data Bus
The actual value of the machine temperature is taken from the Data Bus and used for further calculations in the component.

Selection Button Current Limit
On
Off
If the button is switched on, the actual current is set to the user-defined limit every time it exceeds this limit.

Selection Button Current Limit
On
Off
When the button is switched off, the actual current has no user-defined limit.

Selection Button Control Variable
Load Signal
Desired Torque
In this case the Electric Machine is controlled by Load Signal. The Data Bus Input 'Load Signal' has to be connected.

Selection Button Control Variable

Load Signal

Desired Torque

In this case the electric machine is controlled by desired torque. The Data Bus input 'Desired Torque' has to be connected.

4. **Switches: Machine Maps U_2, …, U_5**

When these switches are deactivated, the user can enter the characteristic maps only for one user-defined constant voltage level U1. If the user activates some of the switches U2…U5, the Characteristic Maps of the machine (maximum power (torque) and efficiency) can be defined in more detail by defining every map dependent on the corresponding voltage level U2…U5 (which could be entered in "Characteristic Maps of Machine"). In this case the actual characteristics are interpolated out of the defined maps.

2.13.2 User-Defined Variables

E_{EM}	Type of Machine	–

The user can select between an ASM (Asynchronous Motor) and a PSM (Permanent magnetic Synchronous Motor).

M_{EM}	Selection switch for Characteristic Maps and Curves	–

Selection between 'motor-related', 'generator-related' and 'overall.'

motor-related: data of the Characteristic Maps have been measured in motoric mode and are referred to the 1st drive quadrant.

generator-related: data of the Characteristic Maps have been measured in generatoric mode and are referred to the 4th drive quadrant.

overall: 4 Quadrants mode; data for all quadrants can be entered. At least data for

one motoric quadrant (1st or 3rd) and for one generatoric quadrant (2nd or 4th) are required. Quadrants with no data are calculated by reflection over the point (0/0).

Nominal Values

$U_{EM,nom}$	Nominal Voltage	V

The Nominal Voltage should be the same as in the onboard network.

$\Theta_{EM,nom}$	Inertia Moment	kg m^2
$I_{EM,mot,max}$	Maximum Current–Motor	A

$\dot{\varphi}_{EM,mot,\max}$	Maximum Speed	1/min

The maximum speed is the maximum angular velocity the electric motor can run at.

$M_{\mathrm{EM,drag}}$	Drag Torque	Nm
$I_{\mathrm{EM,gen,max}}$	Maximum Current–Generator	A

Thermal Model

m_{EM}	Mass of Machine	kg

$T_{\mathrm{EM,init}}$	Initial Temperature	°C

This is the temperature which the electric machine has at calculation start.

$\alpha_{\mathrm{EM,th}}$	Specific Heat Transition	W/K

The specific heat transition sums up all influences (such as material, surface state etc.), which influence the transmission of heat.

$t_{\mathrm{EM,T}}$	Thermal Time Constant of Maximum Power	s

This is the maximum time that the machine can run with maximum power.

The thermal time constant of maximum power is the time duration where the maximum power can be delivered. During this time, the ambient temperature must not increase.

$T_{\mathrm{EM,max}}$	Maximum Temperature	°C
$C_{\mathrm{EM,th}}$	Specific Heat Capacity	J/kg K

The specific heat capacity defines the different heating behavior of the material. It is the energy, which is needed in order to warm up material of 1 kg mass by 1 K (temperature).

$T_{\mathrm{EM,L}}$	Layout Temperature	°C

The layout temperature is the temperature where the electric machine has its highest efficiency.

$\beta_{\mathrm{EM,Rem}}$	Temperature Coefficient of Remanence Induction	1/K

With this coefficient, the influence of the temperature on the remanence induction is defined.

Characteristic Maps of Machine

The value of the voltage level should be entered at which the following Characteristic Maps of the machine have been measured. In addition to the U1 level, up to 4 further levels U2…U5 could be activated in the property window. For each activated level the corresponding voltage value must be defined and the corresponding Characteristic Maps.

U_{EM}	Voltage	V
$P_{EM,U_{EM},max}\left(\dot{\varphi}_{EM,out}\right)$	Maximum Power (Torque) mechanical	kW

Either the maximum mechanical power or the maximum mechanical torque is defined as function of the machine's speed.

$\eta_{EM}\left(P_{EM,U_{EM,act},\varphi_{EM,out}}\right)$.	Efficiency	%

The Efficiency of the electric machine is defined dependent on speed and power (or torque). This has to be defined if the selection button 'Losses' is set to *Efficiency*.

$P_{EM,loss}\left(P_{EM,U_{EM,act},\varphi_{EM,out}}\right)$.	Power Loss	W

The Power Loss of the electric machine is defined dependent on speed and power (or torque). This has to be defined if the selection button 'Losses' is set to *Power Loss.*

2.13.3 Input and Output Variables

2.13.3.1 Mechanical Connections

$\dot{\varphi}_{EMt}$	Angular velocity	rad/s
$\ddot{\varphi}_{EM}$	Angular acceleration	rad/s^2
$\dot{\varphi}_{EM,max}$	Maximum of angular velocity	rad/s
$M_{EM,dt}$	Torque	Nm

2.13.3.2 Electrical Connections

$U_{EM,net}$	Net Voltage	V
I_{EM}	Current	A

2.13.3.3 Data Input

$T_{EM,env}$	Ambient temperature	°C
$T_{EM,ext}$	External temperature	°C
α_{EM}	Load signal	–
$M_{EM,desired}$	Desired Torque	Nm
Z_{EM}	Switch	–

2.13.3.4 Data Output

$U_{EM,net}$	Net Voltage	V
I_{EM}	Current	A
M_{EMt} (T_{EM})	Torque	Nm
$\dot{\varphi}_{\mathbf{EM,out}}$	Angular velocity	rad/s
T_{EM}	Temperature	°C
$M_{EM,max,mot}$	Maximum torque-motor	Nm
$M_{EM,max,gen}$	Maximum torque-generator	Nm
$K_{EM,mode}$	Operating mode	–
K_{EM}	Operating control	–
$K_{EM,overvolt}$	State-Voltage overflow	–
$P_{EM,el}$	Electric Power	W
α_{EM}	Actual Load Signal	–
$P_{EM,mech}$	Mechanical Power	W
$P_{EM,loss}$	Power Loss	W

2.13.4 Computation Variables

$P_{EM,loss,max}$	Maximum loss of power	kW
$P_{EM,loss}$	Actual loss of power	kW
$P_{EM,el}$	Actual electric power	W
$M_{EM,max}$	Maximum torque	Nm
$P_{EM,mech}$	Actual mechanical power	kW

2.13.5 Equation System

2.13.5.1 Mechanical Part

The actual moment of the drivetrain is given by [2]:

$$M_{\mathrm{EM,dt}} = M_{\mathrm{EM}} - \Theta_{\mathrm{EM,nom}}\ddot{\varphi}_{\mathrm{EM,out}} \tag{2.13.1}$$

The following calculation is used for permanent field machines [2]:

$$M_{\mathrm{EM}}(T_{\mathrm{EM}}) = (1 + \beta_{\mathrm{EM,REm}}(T_{\mathrm{EM}} - T_{\mathrm{EM,L}}))M_{\mathrm{EM}}(T_{\mathrm{EM,L}}) \tag{2.13.2}$$

(*drivetrain turned off*) [2]

$$M_{\mathrm{EM}} = M_{\mathrm{EM,drag}}\left(\dot{\varphi}_{\mathrm{EM}}/\dot{\varphi}_{\mathrm{EM,max}}\right)^2 \tag{2.13.3}$$

For permanent field machines the losses of iron have to be taken into consideration.

If the drivetrain is turned on the following calculation is used [2].

$$M_{\mathrm{EM}} = kM_{\mathrm{EM,max,mot}}, \quad \text{if } k > 0, \tag{2.13.4}$$

$M_{\mathrm{EM}} = (-k)M_{\mathrm{EM,max,gen}}$, otherwise.

Special Case: If the torque of the generator is very small or if it is zero, then the drivetrain is in motor-related mode to balance friction torque, etc.

2.13.5.2 Electrical Part

The electric power is given by [2]:

$$P_{\mathrm{EM,el}} = P_{\mathrm{EM,mech}} + P_{\mathrm{EM,loss}}. \tag{2.13.5}$$

The loss of power $P_{\mathrm{EM,loss}}$ *consists of losses of iron, copper, and losses according to friction.*

It is completely transformed into heat. The mechanical power of the drivetrain is defined by [2]:

$$P_{\mathrm{EM,mech}} = \dot{\varphi}_{\mathrm{EM}}M_{\mathrm{EM}} \tag{2.13.6}$$

There are the following conventions of the sign:

If $P_{\mathrm{EM,el}} > 0$, then the motor-related mode is chosen, else if $P_{\mathrm{EM,el}} < 0$, then the generator-related mode is chosen.

There are two possible cases for the loss of power and the efficiency in motor-related mode. There $M_{EM,1}$ and $\dot{\varphi}_{EM,1}$ are the smallest data points in the characteristic map of the machine.

Motor-related losses [2]

If $\boldsymbol{M_{EM,out} > M_{EM,1}}$, $\quad \boldsymbol{\dot{\varphi}_{EM,out} > \dot{\varphi}_{EM,1}}$

$$P_{EM,loss,act} = P_{EM,mech,act}\left(1/_{EM}\left(M_{EM,out}, \dot{\varphi}_{EM,out}\right) - 1\right) \tag{2.13.7}$$

If $\boldsymbol{M_{EM,out} > M_{EM,1}}$, $\quad \boldsymbol{0 < \dot{\varphi}_{EM,out} \leq \dot{\varphi}_{EM,1}}$

$$P_{EM,loss,act} = \dot{\varphi}_{EM,out,1} M_{EM,}\left(1/_{\eta_{EM}}\left(M_{EM,out}, \dot{\varphi}_{EM,out}\right) - 1\right) \tag{2.13.8}$$

Generator-related losses [2]

If $\boldsymbol{M_{EM,1} > \left|M_{EM,drag}\right|}$, **then** $\boldsymbol{M_{EM,1}}$ **is set to** $\boldsymbol{M_{EM,drag}}$.

If $|\boldsymbol{M_{EM}}| \gg 0$, $\quad \boldsymbol{\dot{\varphi}_{EM}} \gg 0$

$$P_{EM,loss} = \left|P_{EM,mech}(1 - \eta_{EM}(M_{EM}, \dot{\varphi}_{EM}))\right| \tag{2.13.9}$$

If $|\boldsymbol{M_{EM}}| \gg \quad 0, \boldsymbol{\dot{\varphi}_{EM}} \cong 0$

$$P_{EM,loss} = \left|\dot{\varphi}_{EM,1} M_{EM}(1 - \eta_{EM}(M_{EM}, \dot{\varphi}_{EM}))\right| \tag{2.13.10}$$

Losses due to small torque [2]

If $M_{EM,out} \gg \quad 0, \dot{\varphi}_{EM,out} \gg 0$

$$P_{EM,loss} = \dot{\varphi}_{EM} M_{EM,1}\left[a(M_{EM})\left(1/_{EM}\left(M_{EM,1}, \dot{\varphi}_{EM}\right) - 1\right) + (1 - a(M_{EM}))\left(1 - \eta_{EM}\left(M_{EM,1}, \dot{\varphi}_{EM}\right)\right)\right] \tag{2.13.11}$$

If $M_{EM,out} \gg \quad 0, \dot{\varphi}\eta_{EM,out} \cong 0$

$$P_{EM,loss} = \dot{\varphi}_{EM} M_{EM,1}\left[a(M_{EM})\left(1/_{\eta_{EM}}\left(M_{EM,1}, \dot{\varphi}_{EM,1}\right) - 1\right) + (1 - a(M_{EM}))\left(1 - \eta_{EM}\left(M_{EM,1}, \dot{\varphi}_{EM,1}\right)\right)\right] \tag{2.13.12}$$

where

$$a(M_{EM}) = \left(M_{EM} - M_{EM,drag}\dot{\varphi}_{EM}{}^2\right)/\left(M_{EM,1} - M_{EM,drag}\dot{\varphi}_{EM}{}^2\right) \tag{2.13.13}$$

The difference between the losses in motor-related mode and the losses in generator-related mode is given by the lowest torque in the Characteristic Map and the drag torque. In the domain above the smallest positive torque the motor-related mode is used and the efficiency is unique defined. In the domain below the negative torque and below the drag torque the generator-related mode is used. In the domain

between the described domains again the motor-related mode is being used. There a smooth transition in the loss of power.

Furthermore the terminal current of the drivetrain is given by [2]:

$$I_{\mathrm{EM}} = P_{\mathrm{EM,el}} / U_{\mathrm{EM,net}} \tag{2.13.14}$$

For the maximal torque the following is defined using the loss of power and [2]:

$$R_{\mathrm{th}} = 1/\alpha_{\mathrm{EM,th}} \tag{2.13.15}$$

$$I_{\mathrm{EM}} = P_{\mathrm{EM,el}} / U_{\mathrm{EM,net}} \tag{2.13.16}$$

$$P_{\mathrm{EM,loss,max}} = \left(T_{\mathrm{EM}} - T_{\mathrm{EM,env}} + \left(T_{\mathrm{EM,max}} - T_{\mathrm{EM}}\right)/\left(1 - \exp\left(-1\left(t_{\mathrm{EM,T}}/\left(C_{\mathrm{EM,th}} R_{th}\right)\right)\right)\right)\right)/R_{\mathrm{th}}. \tag{2.13.17}$$

$$M_{\mathrm{EM,max,mot}} = M_{\mathrm{EM,max,mot}}\left(P_{\mathrm{EM,loss,max}}, I_{\mathrm{EM,mot,max}}\right) \tag{2.13.18}$$

$$M_{\mathrm{EM,max,gen}} = M_{\mathrm{EM,max,gen}}\left(P_{\mathrm{EM,loss,max}}, I_{\mathrm{EM,gen,max}}\right) \tag{2.13.19}$$

Here the complete Characteristic Map is being searched beginning at the maximal permitted torque, until the loss of power is smaller than $P_{\mathrm{EM,loss,max}}$. This value is the maximal permitted torque. The same holds for the generator-related mode.

There the maximal torque is calculated using the maximum of all angular velocities using [2]:

$$M_{\mathrm{EM,max}} = P_{\mathrm{EM,U_{EM},max}}(\dot{\varphi}_{\mathrm{EM}})/\dot{\varphi}_{\mathrm{EM}} \tag{2.13.20}$$

2.13.5.3 Thermal Part

The basic equations of the transition of heat in the electric machine are [2]:

$$\mathrm{d}Q = \mathrm{m_{EM}C_{EM,th}\,dT} = /\mathrm{P_{EM,W}dt} \tag{2.13.21}$$

$\mathrm{P_{EM,W}}$ *is the complete power, which is transformed into heat. It consists of the heat power due to electric losses and due to the heat transition to the environment* [2]:

$$P_{\mathrm{W}} = P_{\mathrm{EM,loss}} + P_{\mathrm{EM,env}} \tag{2.13.22}$$

and [2]:

$$P_{\mathrm{EM,env}} = \alpha_{\mathrm{EM,th}}\left(T_{\mathrm{EM}} - T_{\mathrm{EM,env}}\right) \tag{2.13.23}$$

2.14 Battery H (QH)

Together with the components supercapacitor and electric machine, the component battery H is used for modeling hybrid vehicles.

The basic model consists of a voltage source and a resistance. The resistance is constructed that way that complex processes within the battery can be considered.

2 RC elements can be added optionally. They describe the concentration overvoltage and the transition overvoltage.

Also, the resistance's dependence on the temperature can be activated optionally.

There can be modeled single cells as well as a combination of them. Therefore, any modules can be constructed [1].

The thermal behavior of the battery is described by a thermal model. Here, the warming caused by the losses and the cooling caused by convection is taken under consideration [1].

2.14.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Temperature
Calculated
From Data Bus
The battery's temperature is calculated by the component using a thermal model.

Selection Button Temperature
Calculated
From Data Bus
The actual value of the battery's temperature which has been calculated externally is taken from the Data Bus and used for further calculations in the component.

Selection Button Ohmic Resistances
Constant
Temperature Dependent
Temperature and SOC Dependent
The constant values are used for the calculation.

Selection Button Ohmic Resistances
Constant
Temperature Dependent
Temperature and SOC Dependent
In this case the temperature-dependent maps for the internal resistances are used.

Selection Button Ohmic Resistances

Constant

Temperature Dependent

Temperature and SOC Dependent

In this case, up to 5 'Battery Characteristics—Temperature and SOC Dependent' can be used where each is associated with a user-defined constant temperature value. During calculation in every time step an interpolation between these characteristics is done to generate temperature-dependent values.

Switch Coulombic Efficiency

This switch can only be activated if the selection button **Ohmic Resistances** is set to temperature and SOC dependent.

If this switch is selected, the coulombic efficiency in charge mode can be defined dependent on the State of Charge. This can be defined for up to 5 temperature levels.

Switch Resistances RC Concentration Overvoltage

By activating this switch, the RC concentration overvoltage resistances are taken into consideration during the calculation.

Switch Resistances RC Transfer Overvoltage

By activating this switch, the RC transfer overvoltage resistances are taken into consideration during the calculation.

Switch Characteristics T1–T5

With these switches, the associated 'Battery Characteristics—Temperature and SOC Dependent' can be activated for up to 5 temperature levels. This selection is only available if the selection button **Ohmic Resistances** is set to *Temperature and SOC Dependent.*

2.14.2 User-Defined Variables

Nominal Values of Cell

$Q_{QH,max}$	Maximum Charge	A s
$Q_{QH,init}$	Initial Charge	%

The initial charge is the charge the cell has at the beginning of the calculation. It is defined as percentage of the maximum charge.

$U_{QH,nom}$	Nominal Voltage	V

The nominal voltage of the cell depends on the used material.

$U_{QH,max}$	Maximum Voltage	V

The actual voltage of the cell should not exceed the defined value of the maximum voltage.

$U_{QH,min}$	Minimum Voltage	V

The actual voltage of the cell should not be lower than the defined value of the minimum voltage.

Number of Cells

$N_{QH,cells_in_row}$	Number of Cells per Cell-Row	–
$N_{QH,cell_rows}$	Number of Cell-Rows	–

The battery's cell structure is kind of a matrix with a constant number of rows and a constant number of cells in each row.

Thermal Model

$T_{QH,op}$	Operating Temperature	K

This is the temperature where the battery has its highest efficiency.

$m_{QH,cell}$	Mass of a Cell	kg
$\alpha_{QH,th,trans}$	Specific Heat Transition	W/K

The specific heat transition summarizes all influences (such as material, surface state, conductivity) which influence the transmission of heat.

$C_{QH,th}$	Specific Heat Capacity	J/kg K

The specific heat capacity defines the different heating behaviors of the material. It is the energy which is needed in order to warm up material of 1 kg mass by 1 K.

Characteristic Maps of Machine

$U_{QH,idle,charge}(Q_{QH,act})$	Idle Voltage—Charge	V

The idle voltage—charger is the idle voltage of one cell in charge mode. There is no electrical consumer. It is a function of the SOC.

$U_{QH,idle,discharge}(Q_{QH,act})$	Idle Voltage—Discharge	V

The idle voltage—discharge of one cell is the voltage without an electrical consumer that means there is no flow of the current. It is a function of the SOC.

$R_{QH,charge}(T_{QH,act})$	Ohmic Resistance—Charge	Ohm

The ohmic resistance—charge is the internal resistance of one cell in charge mode. It is a function of the temperature of the battery. If the switch resistances temperature dependent is switched off, then only a fixed value is needed.

$R_{QH,discharge}(T_{QH,act})$	Ohmic Resistance—Discharge	Ohm

The ohmic resistance—discharge is the internal resistance of one cell in discharge mode. It is a dependent on the temperature of the battery. If the switch resistances temperature dependent is switched off, then only a fixed value is needed.

$C_{QH,conc,charge}$	Capacity of RC Concentration Overvoltage—Charge	A s/V

The capacity of RC concentration—charge is the nominal capacity of the RC concentration overvoltage in charge mode.

This input is only needed if the switch resistances RC concentration overvoltage is activated.

$R_{QH,conc,charge}(T_{QH,act})$	Resistance of RC Concentration Overvoltage—Charge	Ohm

The resistance RC concentration overvoltage—charge is the internal resistance of the RC concentration overvoltage in charge mode. It is defined as a function of the temperature of the battery. This input is only needed if the switch resistances RC concentration overvoltage is activated. Additionally, only a fixed value is needed, if the switch resistances temperature dependent is switched off.

$C_{QH,conc,discharge}$	Capacity of RC Concentration Overvoltage—Discharge	A s/V

The capacity of RC concentration—discharge is the nominal capacity of the RC concentration overvoltage in discharge mode. This input is only needed if the switch resistances RC concentration overvoltage is activated.

$R_{QH,conc,discharge}(T_{QH,act})$	Resistance of RC Concentration Overvoltage—Discharge	Ohm

The resistance RC concentration overvoltage—discharge is the internal resistance of the RC concentration overvoltage in discharge mode. It is defined as a function of the temperature of the battery. This input is only needed if the switch

resistances RC concentration overvoltage is activated. Additionally, only a fixed value is needed, if the switch resistances temperature dependent is switched off.

$C_{QH,trans,charge}$	Capacity of RC Transfer Overvoltage—Charge	A s/V

The capacity of RC transfer—charge is the nominal capacity of the RC transfer overvoltage in charge mode. This input is only needed if the switch resistances RC concentration overvoltage is activated.

$R_{QH,trans,charge}(T_{QH,act})$	Resistance of RC Transfer Overvoltage—Charge	Ohm

The resistance RC transfer overvoltage—charge is the internal resistance of the RC transfer overvoltage in charge mode. It is defined as a function of the temperature of the battery. This input is only needed if the switch resistances RC transfer overvoltage is activated. Additionally, only a fixed value is needed, if the switch resistances temperature dependent is switched off.

$C_{QH,trans,discharge}$	Capacity of RC Transfer Overvoltage—Discharge	A s/V

The capacity of RC transfer—discharge is the nominal capacity of the RC transfer overvoltage in discharge mode. This input is only needed if the switch resistances RC concentration overvoltage is activated.

$R_{QH,trans,discharge}(T_{QH,act})$	Resistance of RC Transfer Overvoltage—Discharge	Ohm

The resistance RC transfer overvoltage—discharge is the internal resistance of the RC transfer overvoltage in discharge mode. It is defined as a function of the temperature of the battery. This input is only needed if the switch resistances RC transfer overvoltage is activated. Additionally, only a fixed value is needed, if the switch resistances temperature dependent is switched off.

Battery Characteristics—Temperature and SOC Dependent

The following input is only required if the selection button **Ohmic Resistances** is set to *Temperature and SOC Dependent*.

$T_{G,i}$	Temperature i = 1, …, 5	°C

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the temperature level has to be specified.

$U_{QH,idle,charge,i}(Q_{QH,act})$	Idle Voltage—Charge i = 1, …, 5	V
$U_{QH,idle,discharge,i}(Q_{QH,act})$	Idle Voltage—Discharge i = 1, …, 5	V

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the idle voltage has to be defined depending on the State of Charge.

$R_{QH,charge,i}(Q_{QH,act})$	Ohmic Resistance—Charge i =, …, 5	Ohm
$R_{QH,discharge,i}(Q_{QH,act})$	Ohmic Resistance—Discharge i =, …, 5	Ohm

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the ohmic resistance has to be defined depending on the State of Charge.

$\eta_{QH,charge,i}(Q_{QH,act})$	Coulombic Efficiency—Charge i = 1, …, 5	%

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the coulombic efficiency in charge mode has to be defined depending on the State of Charge.

$R_{QH,conc,charge,i}(Q_{QH,act})$	Resistance of RC Concentration Overvoltage—Charge i = , …, 5	Ohm
$R_{QH,conc,discharge,i}(Q_{QH,act})$	Resistance of RC Concentration Overvoltage—Discharge i = , …, 5	Ohm

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the resistance of RC concentration overvoltage has to be defined depending on the State of Charge.

$R_{QH,trans,charge,i}(Q_{QH,act})$	Resistance of RC Transfer Overvoltage—Charge i = , …, 5	Ohm
$R_{QH,trans,discharge}(Q_{QH,act})$	Resistance of RC Transfer Overvoltage—Discharge	Ohm

For each activated, temperature depending 'battery characteristics—temperature and SOC dependent', the resistance of RC transfer overvoltage has to be defined depending on the State of Charge.

2.14.3 Input and Output Variables

2.14.3.1 Electrical Connections

I_{QH}	Actual Battery Current	A
$U_{QH,net}$	Actual Net Voltage	V

2.14.3.2 Data Input

$T_{QH,ambient}$	Ambient Temperature	°C

(continued)

$T_{QH,extern}$	Temperature external	°C
Z_{QH}	Switch	–

2.14.3.3 Data Output

$U_{QH,net}$	Net Voltage	V
I_{QH}	Current	A
Q_{QH}	Battery Charge	A s
SOC_{QH}	State of Charge	A s
T_{QH}	Temperature	°C
$Z_{QH,overcharge}$	Status—Overcharge	–
$Z_{QH,overvoltage}$	Status—Overvoltage	–
$Z_{QH,undervoltage}$	Status—Undervoltage	–
P_{QH}	Power	W
$P_{QH,loss}$	Power Loss	W

2.14.4 Computation Variables

$U_{QH,terminal}$	Terminal Voltage of a cell	V
$U_{QH,idle}$	Idle Voltage of a cell	V
$I_{QH,terminal}$	Terminal Current of a cell	A
SOC_{QH}	State of Capacity of a cell	–
$I_{QH,ohmic}$	Actual Current through cell	A
$Q_{QH,conc}$	Charge of RC Concentration Overvoltage	A s
$Q_{QH,trans}$	Charge of RC Transfer Overvoltage	A s
Q_{QH}	Actual Charge of the cell	A s
$I_{QH,ohmic,trans}$	Current through resistance of RC Transfer Overvoltage	A
$I_{QH,ohmic,conc}$	Current through ohmic resistance of RC Concentration Overvoltage	A
$I_{QH,max,charge}$	Maximum Current in charge mode	A
$I_{QH,max,discharge}$	Maximum Current in discharge mode	A
$P_{QH,out,max}$	Maximum Power out	W
$P_{QH,in,max}$	Maximum Power in	W
$P_{QH,th}$	Total thermal Power	W
$P_{QH,th,el}$	Thermal Power within the cell	W
$P_{QH,th,ambient}$	Thermal Power transferred to the environment	W
$T_{QH,bat}$	Actual Temperature of the battery	°C
$T_{QH,ambient}$	Actual ambient Temperature	°C

2.14.5 Equation System

Through an internal calculation it is possible to use one single cell as well as any combination of cells. Therefore the user can construct any desired module.

2.14.5.1 Electrical Equations

The electrical equations of a battery cell are described as follows [2]:

$$U_{\mathrm{QH,terminal}} = U_{\mathrm{QH,idle}}\left(I_{\mathrm{QH,terminal}}, \mathrm{SOC}\right) - I_{\mathrm{QH,ohmic}} \cdot R_{\mathrm{QH}}\left(I_{\mathrm{QH,terminal}}\right) - Q_{\mathrm{QH,conc}}/C_{\mathrm{QH,conc}} - Q_{\mathrm{QH,trans}}/C_{\mathrm{QH,trans}} \tag{2.14.1}$$

$$I_{\mathrm{QH,ohmic,trans}} = Q_{\mathrm{QH,trans}}/\left(C_{\mathrm{QH,trans}} \cdot R_{\mathrm{QH,trans}}\right) \tag{2.14.2}$$

$$I_{\mathrm{QH,ohmic,conc}} = Q_{\mathrm{QH,conc}}/\left(C_{\mathrm{QH,conc}} \cdot R_{\mathrm{QH,conc}}\right) \tag{2.14.3}$$

Here the current influences the idle voltage and the resistance only by its sign. The maximal currents of the battery cell are calculated by [2]:

$$I_{\mathrm{QH,max,charge}} = \left(U_{\mathrm{QH,idle,charge}}\left(I_{\mathrm{QH,terminal}}, SOC\right) - U_{\mathrm{QH,max}} - Q_{\mathrm{QH,conc}}/C_{\mathrm{QH,conc}} - Q_{\mathrm{QH,trans}}/C_{\mathrm{QH,trans}}\right)/R_{QH}\left(I_{\mathrm{QH,terminal}}\right). \tag{2.14.4}$$

and [2]:

$$I_{\mathrm{QH,max,discharge}} = \left(U_{\mathrm{QH,idle,discharge}}\left(I_{\mathrm{QH,terminal}}, \mathrm{SOC}\right) - U_{\mathrm{QH,min,discharge}} - Q_{\mathrm{QH,conc}}/C_{\mathrm{QH,conc}} - Q_{\mathrm{QH,trans}}/C_{\mathrm{QH,trans}}\right)/R_{\mathrm{QH}}\left(I_{\mathrm{QH,terminal}}\right) \tag{2.14.5}$$

with [2]:

$$\mathrm{SOC}_{\mathrm{QH}} = Q_{\mathrm{QH}}/Q_{\mathrm{QH,max}} \tag{2.14.6}$$

The initial values are calculated by [2]:

$$Q_{\mathrm{QH,init}} = \mathrm{SOC}_{\mathrm{QH,init}} \cdot Q_{\mathrm{QH,max}} \tag{2.14.7}$$

The maximum power in and maximum power out are calculated in a numerical way by searching for the maximum within the functions [2]:

$\boldsymbol{P_{\mathrm{QH,out,max}}}\left(\boldsymbol{U_{\mathrm{QH,min,discharge}}}, \boldsymbol{I_{\mathrm{QH,terminal}}}\right)$ and $\boldsymbol{P_{\mathrm{QH,in,max}}}\left(\boldsymbol{U_{\mathrm{QH,max,charge}}}, \boldsymbol{I_{\mathrm{QH,terminal}}}\right)$

2.14.5.2 Thermal Equations

The basic equation for the heating within a material is [2]:

$$\mathrm{d}Q = m_{\mathrm{QH,cell}} \cdot C_{\mathrm{QH,heat}} \mathrm{d}T_{\mathrm{QH,bat}} = P_{\mathrm{QH,th}} \mathrm{d}t \tag{2.14.8}$$

Here, $P_{\mathrm{QH,th}}$ is the total power that is converted into heat. It consists of the heat power inside the cell caused by electrical losses and of the heat transfer to the environment [2]:

$$\mathrm{P}_{\mathrm{QH,th}} = \mathrm{P}_{\mathrm{QH,th,el}} + \mathrm{P}_{\mathrm{QH,th,ambient}} \tag{2.14.9}$$

and it is [2]:

$$P_{\mathrm{QH,th,ambient}} = \alpha_{\mathrm{QH,th,trans}} \left(T_{\mathrm{QH,bat}} - T_{\mathrm{QH,ambient}} \right) \tag{2.14.10}$$

and [2]:

$$\begin{aligned} P_{\mathrm{QH,th,el}} = {} & I^2_{\mathrm{QH,ohmic}} \cdot R_{\mathrm{QH}} + I^2_{\mathrm{QH,ohmic,trans}} \cdot R_{\mathrm{QH,trans}} + I^2_{\mathrm{QH,conc}} \left(T_{\mathrm{QH,act}} \right) \cdot R_{\mathrm{QH,conc}} \\ & + \left| 0.5 I_{\mathrm{QH,terminal}} \cdot \left(U_{\mathrm{QH,idle}} \left(I_{\mathrm{QH,terminal}} \cdot \mathrm{SOC}_{\mathrm{QH}} \right) - U_{\mathrm{QH,idle}} \left(-I_{\mathrm{QH,terminal}}, \mathrm{SOC}_{\mathrm{QH}} \right) \right) \right| \end{aligned} \tag{2.14.11}$$

with the last term describing the losses caused by the polarization voltage.

2.15 Gearbox Control (O)

The gearbox control is needed to define an automatic gearbox. In the gearbox control, the gear shifting process can be defined automatically without any influence of the driver [1].

The gearbox control shifts the gears dependent on a speed or a velocity. The decision which one of the two shifting strategies is used is done in the calculation tasks. Which speed, respectively which velocity is used can be defined via the Data Bus. It is possible to define the engine speed but it is also possible to define the wheel speed as reference [1].

The gearbox control is also the connection between the gearbox program and the gearbox [1].

2.15.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Switch Time Delay Gear Dependent
If this switch is activated, the time delay between the start of a shifting procedure and the start of a gear change can be defined gear dependent.

This functionality is necessary especially for automatic gearboxes or Shift by Wire (Step-Tronic).

Switch Skipping Gear(s) For Upshifting Allowed
When this switch is activated, then the highest gear satisfying the shifting condition will be shifted, thus more than one gear step could be skipped.

Switch Skipping Gear(s) For Downshifting Allowed
When this switch is activated, then the lowest gear satisfying the shifting condition will be shifted, thus more than one gear step could be skipped.

The following Selection Buttons are only used for Task 'System Analysis Mode (SAM)':

Selection Button SAM
Shifting Strategy
Gearbox Control
For automatic cockpits it can be determined that the gearbox control controls the gear shifting process.

Gear Shifting Program
For automatic cockpits it can be determined that the gearbox program controls the gear shifting process.

Selection Button SAM
Gear Selection Upshifting
According to Velocity
The values for shifting gears according to velocity as defined for the driver (manual cockpit or pressed Tiptronic switch for automatic cockpits) or with gear box control (automatic cockpit and deactivated Tiptronic switch) are activated.

According to Speed
The values for shifting gears according to speed as defined for the driver (manual cockpit or pressed Tiptronic switch for automatic cockpits) or with gear box control (automatic cockpit and deactivated Tiptronic switch) are activated.

Selection Button SAM
Gear Selection Downshifting
This selection button has to be selected analog to the button **SAM: Gear Selection Upshifting**.

2.15.2 User-Defined Variables

Gear Shifting according to Velocity

$v_{O,inc}[n]$	Upshifting Velocity $v_{O,inc}[n]$ for the nth gear	km/h
$v_{O,decr}[n]$	Downshifting Velocity $v_{O,decr}[n]$ for the nth gear	km/h

The velocities for up- and downshifting can be read e.g. in the following way:

The upshifting velocity of the 2nd gear means that at this velocity the gearbox control is upshifting from the 2nd into the 3rd gear. The downshifting velocity for the 2nd gear means that at this velocity the gearbox control is downshifting from the 3rd into the 2nd gear. Therefore it is necessary to define the up- and downshifting velocities always only for one gear less than are available in the gearbox (i.e., for a five step gearbox, only for four gears the up- and downshifting velocities have to be defined).

Gear Shifting according to Speed

$\dot{\varphi}_{O,incr}[i]$	Upshifting Speed $\dot{\varphi}_{O,incr}[i]$ for the nth gear	rpm
$\dot{\varphi}_{O,decr}[i]$	Downshifting Speed $\dot{\varphi}_{O,decr}[i]$ for the nth gear	rpm

Similar to the shifting according to velocity the speeds for up- and downshifting can be read e.g. in that way:

The upshifting speed of the 2nd gear means that at this speed the gearbox control is upshifting from the 2nd into the 3rd gear. The downshifting speed for the 2nd gear means that at this speed the gearbox control is downshifting from the 3rd into the 2nd gear.

Therefore it is necessary to define the up- and downshifting speeds always only for one gear less than are available in the gearbox (i.e., for a five step gearbox, only for four gears the up- and downshifting speeds have to be defined).

Gear Shifting according to Speed of next Gear

$\dot{\varphi}_{O,incr,next}[i]$	Upshifting Speed of next Gear for the nth gear	rpm
$\dot{\varphi}_{O,decr,next}[i]$	Downshifting Speed of next Gear for the nth gear	rpm

Here the upshifting and downshifting speeds of the next gear are defined separate for each gear.

Delay Time Gear Dependent

$T_{O,delay,incr}[i]$	Upshifting delay time for the ith gear	s
$T_{O,delay,decr}[i]$	Downshifting delay time for the ith gear	s

Here the upshifting and downshifting time delays are defined separately for each gear. Shifting procedures which are not described in the table get the time delay 0.

2.15.3 Input and Output Variables

2.15.3.1 Data Input

$Z_{\text{cont,up}}$	Gear Selection Upshifting	–
$Z_{\text{cont,dn}}$	Gear Selection Downshifting	–
$j_{\text{O,targ}}$	Desired Gear (Cockpit)	–
$j_{\text{O,actual}}$	Current Gear	–
$v_{\text{V,act}}$	Velocity	km/h
$\dot{\varphi}_{\text{ref,act}}$	Reference Speed	rad/s
Z_{operate}	Operation Control	–
$j_{\text{O,prog}}$	Desired Gear (Gearbox Program)	–

2.15.3.2 Data Output

$j_{\text{O,new}}$	Desired Gear	–
$t_{\text{O,delay}}$	Time Delay Gear Dependent	s

2.15.4 Computation Variables

$j_{\text{G,new/up}}$	New gear up	–
$j_{\text{G,new,dn}}$	New gear down	–

2.15.5 Equation System

The gear shifting strategy up ($Z_{\text{cont,up}}$) and down ($Z_{\text{cont,dn}}$) has the information from where the gearbox control should take the target gear:

- profile shifting
- velocity shifting
- speed shifting
- program shifting

2.15.5.1 Profile Shifting

The target gear position comes from the driving profile [2]:

$$\text{If } \left(j_{\text{G,target}} \geq j_{\text{G,act}}\right) \rightarrow j_{\text{G,new,up}} = j_{\text{G,target}} \tag{2.15.1}$$

$$\text{If } \left(j_{\text{G,target}} \leq j_{\text{G,act}}\right) \rightarrow j_{\text{G,new,dn}} = j_{\text{G,target}} \tag{2.15.2}$$

2.15.5.2 Velocity Shifting

The reference is the vehicle velocity [2].

$$\text{If } \left(j_{\text{G,act}} < N_{\text{G}}\right) \wedge \left(V_{\text{v,act}} \geq V_{\text{o,incr}}\lfloor j_{\text{G,act}} \rfloor\right) \rightarrow j_{\text{G,new,up}} = j_{\text{G,act}} + 1 \tag{2.15.3}$$

$$\text{If } \left(j_{\text{G,act}} > 1\right) \wedge \left(V_{\text{v,act}} \leq V_{\text{o,decv}}\lfloor j_{\text{G,act}} \rfloor\right) \rightarrow j_{\text{G,new,dn}} = j_{\text{G,act}} - 1 \tag{2.15.4}$$

2.15.5.3 Speed Shifting

Each angular velocity could be selected via Data Bus for the reference speed [2].

$$\text{If } \left(j_{\text{G,act}} < N_{\text{G}}\right) \wedge \left(\dot{\varphi}_{\text{ref,act}} \geq \dot{\varphi}_{\text{o,incr}}\lfloor j_{\text{G,act}} \rfloor\right) \rightarrow j_{\text{G,new,up}} = j_{\text{G,act}} + 1 \tag{2.15.5}$$

$$\text{If } \left(j_{\text{G,act}} > 1\right) \wedge \left(\dot{\varphi}_{\text{ref,act}} \leq \dot{\varphi}_{\text{o,deu}}\lfloor j_{\text{G,act}} \rfloor\right) \rightarrow j_{\text{G,new,dn}} = j_{\text{G,act}} - 1 \tag{2.15.6}$$

2.15.5.4 Program Shifting

The shifting information is taken from the shifting program.
For up- and downshifting [2]:

$$\text{If } \left(j_{\text{G,prog}} \geq j_{\text{G,act}}\right) \rightarrow j_{\text{G,new,up}} = j_{\text{G,prog}} \tag{2.15.7}$$

$$\text{If } \left(j_{\text{G,prog}} \leq j_{\text{G,act}}\right) \rightarrow j_{\text{G,new,dn}} = j_{\text{G,prog}} \tag{2.15.8}$$

The new gear position is chosen as follows [2]:

$$\text{If } \left(j_{\text{G,new,up}} \geq j_{\text{G,act}} + 1\right) \rightarrow j_{\text{G,new}} = j_{\text{G,act}} + 1 \tag{2.15.9}$$

$$\text{else if } \left(j_{\text{G,new,dn}} \leq j_{\text{G,act}} - 1\right) \rightarrow j_{\text{G,new}} = j_{\text{G,act}} - 1 \tag{2.15.10}$$

$$\text{else} \rightarrow j_{\text{G,new}} = j_{\text{G,act}} \tag{2.15.11}$$

2.16 Gearbox Program (P)

Is used for automatic gearboxes in combination with the gearbox control.

The gearbox program allows for a more complicated gear shifting process than the gearbox control, because here in addition the load signal of the engine is considered [1].

The gearbox program shifts the gears according to given curves. The curves are given as a function of the load signal and the engine speed. The target gear determined by the program is transmitted to the gearbox control that transmits it to the gearbox. Furthermore the curves could be optimized using iSIGHT. These optimized curves (optimized shifting program) could also be used as input curves for the gearbox program [1].

2.16.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

Switch Optimized Shifting Program
By activating this switch the optimized shifting table is used in the gearbox program. (An optimized shifting table must be established using "Start Optimization of Shifting Program".)

Selection Button Shifting Program Selection
Default
Optimized
Advanced
In this case up to five shifting programs can be defined.

Selection Button Shifting Program Selection
Default
Optimized
Advanced
In this case a shifting program is activated which can be optimized with iSIGHT.

Selection Button Shifting Program Selection
Default
Optimized
Advanced
In this case up to five shifting programs and up to five kick down tables can be defined.

Remark: the advanced shifting programs import gear shifting data generated by the task 'GSP Generation'.

Switch Shifting Program 2–5 (Data Bus Dependent)
With these switches the additional defined shifting programs (from 2 up to 5, default or advanced) can be activated. With the Data Bus input 'Shifting Program Selector' (which provides a double value), interpolations between the shifting programs can be done.

Switch Kickdown
With this switch the kickdown table is activated. If the 'Advanced Shifting Program Selection' has been done, up to 5 kickdown tables can be activated.

Switch Shift Remaining Time
When this switch is activated, the remaining time for upshifting and downshifting for every gear can be defined. The remaining time is the minimal time after the shift decision, in which no further shifting is allowed.

2.16.2 User-Defined Variables

Shifting Programs Standard

Shifting Program

$\dot{\varphi}_{\mathrm{P,incr}}\left[n, \alpha_{\mathrm{E,dk}}\right]$ or $v_{\mathrm{P,incr}}\left[n, \alpha_{\mathrm{E,dk}}\right]$	Upshifting Speed (Velocity) dependent on the gear and the load signal	rpm or km/h
$\dot{\varphi}_{\mathrm{P,decr}}\left[n, \alpha_{\mathrm{E,dk}}\right]$ or $v_{\mathrm{P,decr}}\left[n, \alpha_{\mathrm{E,dk}}\right]$	Downshifting Speed (Velocity) dependent on the gear and the load signal	rpm or km/h

The gear shifting process is done similar to the gearbox control. The only difference is the dependence on the load signal of the engine.

If the shifting program should be defined not by speed but by velocity, the Data Bus input 'Velocity' must be connected. The units of the shifting program and the optimized shifting program influence each other. That means, if one of these programs is loaded with a different unit, also the other program gets this new unit.

The speeds for up- and downshifting can be read e.g. in the following way:

The upshifting speed of the 2nd gear with the special load signal means that at this speed with this load signal the gearbox control is upshifting from the 2nd into the 3rd gear.

The downshifting speed for the 2nd gear with the special load signal means that at this speed with this load signal the gearbox control is downshifting from the 3rd into the 2nd gear. Because it is not possible to define the shifting speeds for every possible load signal the characteristic will be interpolated between the given points.

It is only necessary to define the up- and downshifting speeds always for one gear less than are available in the gearbox (i.e., for a five step gearbox, only for four gears the up- and downshifting speeds have to be defined).

Shifting Programs 2–5

$\dot{\varphi}_{P,incr}[n, \alpha_{E,dk}]$ or $v_{P,incr}[n, \alpha_{E,dk}]$	Upshifting Speed 2–5 (Velocity) dependent on the gear and the load signal	rpm or km/h
$\dot{\varphi}_{P,decr}[n, \alpha_{E,dk}]$ or $v_{P,decr}[n, \alpha_{E,dk}]$	Downshifting Speed 2–5 (Velocity) dependent on the gear and the load signal	rpm or km/h

With the properties switches 'Shifting Program 2–5' up to four additional shifting programs can be defined.

With the Data Bus input 'Shifting Program Selector' (which provides a double value), interpolations between the defined shifting programs can be done.

Optimized Shifting Program

β_1	Weight for the penalty term "Performance" in the objective function	–
β_3	Weight for the penalty term "Driveability" in the objective function	–

Regarding the minimization of the fuel consumption and the minimization of the Full Load Acceleration time in standard driving cycles, it is possible to optimize the Gear Shifting Program. Furthermore the driving performance should be improved and the shifting process which should be optimized is equal to the normal gear shifting process (see Fig. 2.16).

Figure 2.16 shows a typical gear shifting map. The green line is for downshifting, the red one for upshifting of the gear. The first lines are the change between the gears one and two, second pair between two and three and so on. This means, if the actual speed is lower than the most left green line, then the gear is changed from the second to the first gear, and if it is larger than the first red one, then the gear is changed from the first to the second gear.

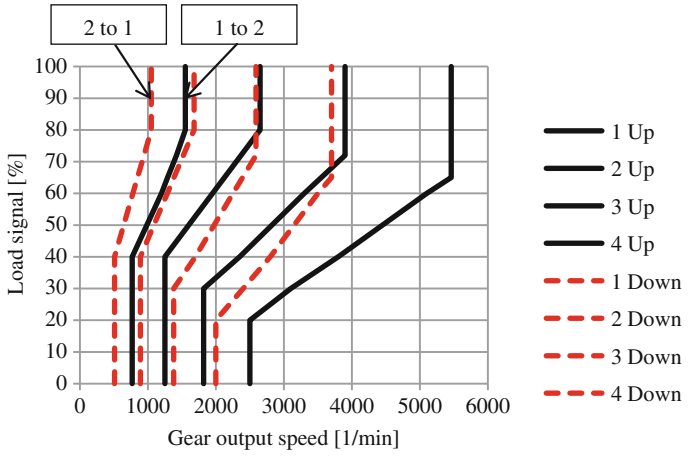


Fig. 2.16 Gear shifting map example. (*dashed red* down shifting, *black* up shifting) [2]

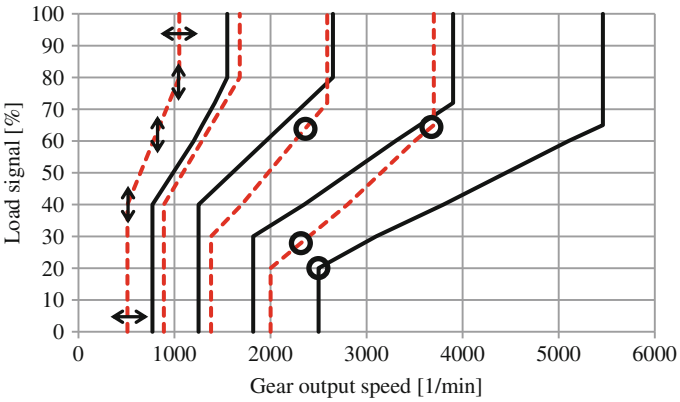


Fig. 2.17 Restrictions in the Gear Shifting Program [2]

The discretized gear shifting map has between 80 and 100 unknowns, depending on the refinement level of the gear shifting map in the input data.

The following figure denotes the possible movements of the unknowns (discretization node). The horizontal lines can move to the right and left and the inner points may move up and down.

The limits for the movements are for the inner points the neighbor points of the same line and for the horizontal lines the corresponding other line (the up for the down line and vice versa) such that there is still a hysteresis in the curve.

This is needed for the decision of the Gear Shifting Program about up or downshifting for an actual speed of the vehicle (Fig. 2.17).

The fuel consumption is given by the calculation of the driving cycle in liters per 100 km as calculated in the task for the cycle. To the optimization objective different penalty terms are added to introduce some regularization of the performance and the result.

The objective function for the fuel optimization is [2]:

$$J = \text{afc} + \beta_1 \int\limits_{\text{time}} (v_{\text{actual}} - v_{\text{desired}})^2 \mathrm{d}t + \beta_2 \int\limits_{\text{time}} |\text{gear}'| \mathrm{d}t + \beta_3 \int\limits_{\text{time}} |\text{acceleration}'| \mathrm{d}t. \tag{2.16.1}$$

where the weight β_2 is calculated according to the input of β_1 and β_3

The penalty terms stand for the driving accuracy (the difference between the actual velocity and the desired velocity should be minimized), measuring the number of gear changes to avoid oscillations and the drivability avoiding large changes in the acceleration of the car.

For the Full Load Acceleration optimization the sum over the velocity measure points is minimized. The measure points τ_i describe the time, when a prescribed velocity is reached.

The objective function is the sum over all measure points $\sum \tau_i$.

For the optimization of the fuel consumption different driving cycles can be included. Thereby a wider range of the gear shifting map may be covered. For the Full Load Acceleration 100 % of the gas pedal as well as smaller values are possible, as it can be configured in the task.

Velocity measure points which are not reached with the initial gear shifting map are ignored. Afterwards only modifications are allowed such that all velocity measure points are reached.

The data preparation is similar to the preparation for a normal calculation of the model in AVL CRUISE, only that some input data now has a special meaning.

The driving cycles now determine the fuel consumption for the objective, similar with the Full Load Acceleration. Other tasks are not taken into consideration.

At least one driving cycle or one Full Load Acceleration task has to be active. Only the active ones are taken into account.

As described for the Full Load Acceleration the objective function in this case is determined through the velocity measure points. The measure points which are defined in the task then describe also the objective function for the optimization.

The subdivisions in the gear shifting map of the gear shifting program determine the number of unknowns. Each of the divisions is taken as unknown, one for the upshifting and one for down. The finer the map the more unknowns.

After the optimization run the result can be loaded using the switch "Optimized Shifting Program" in the properties box. About the result calculated by the optimization routines one has to note that only active parts of the gear shifting map are adapted.

This means only those parts who have an effect on the result may be different from the original one. The other parts are not changed. This may lead to some sharp bends in the curve.

Since iSIGHT is a standalone program it is possible to start other AVL CRUISE processes which are not related to the optimization process during optimization takes place. Due to the fact that the objective function (2.16.1) includes all characteristics of the vehicle and its parts with the connections, no smoothness assumptions are valid for the objective function.

Consequently the direct application of gradient based methods is avoided and a line search in coordinate direction (meaning every unknown) is used to achieve a decrease of the objective function in a stable way in a first step. For every calculation of the objective values AVL CRUISE (optimization kernel calls) must be called (see Fig. 2.18).

For the optimization within iSIGHT a Sequential Quadratic Programming (SQP) method (NLPQL by Prof. Dr. K Schittkowsi) is used which is described shortly below.

NLPQL solves smooth nonlinear problems under nonlinear equality and inequality constraints, i.e. [2]:

min f(**x**)

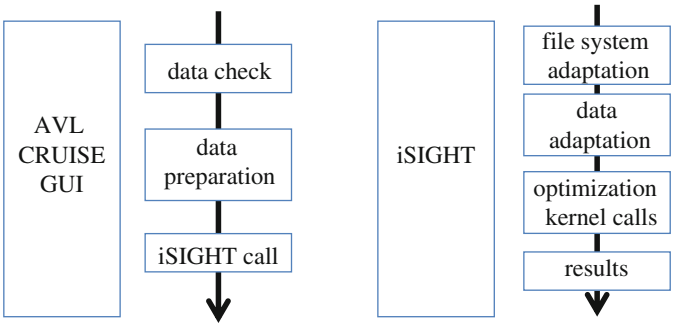


Fig. 2.18 iSIGHT is called for optimization in AVL CRUISE [2]

$$x \in \mathrm{IR}^{\mathrm{n}} : g_j(x) = 0, j = 1, \ldots, m_{\mathrm{e}} \tag{2.16.2}$$

$$g_j(x) \geq 0, j = m_{\mathrm{e}} + 1, \ldots, m$$
$$x_l \leq x \leq x_{\mathrm{u}}$$

where x is an n-dimensional parameter vector (see discretization nodes) with the lower bound x_l and the upper bound x_{u}. These are not handled separately, but considered as general inequality constraints. Since the objective function $f(x)$ and the constraints $g_j(x)$ are continuously differentiable and the problem is not too big NLPQL has proved to find the local minimum of the minimization problem very efficiently. None the less it has to be stated that it is necessary to find start values sufficiently close to the optimum.

The basics of SQP algorithms is described in more detail below:

The idea of this algorithm is to formulate and solve a quadratic programming sub problem in each iteration which is obtained by linearizing the constraints and approximating the Lagrangian function [2]:

$$L(x, u) := f(x) - \sum_{j=1}^{m} \mathrm{u}_j \mathrm{g}_j(\mathrm{x}). \tag{2.16.3}$$

quadratically, where $x \in \mathrm{IR}^n$, and where $u = (u_1, \ldots, u_m)^T \in \mathrm{IR}^m$ is the multiplier vector.

To formulate the quadratic subproblem, it will be proceeded from given iterates $x_k \in \mathrm{IR}^n$, an approximation of the solution, $v_k \in \mathrm{IR}^m$ and approximation of the multipliers, and $\mathrm{B}_k \in \mathrm{IR}^{nxn}$ an approximation of the Hessian of the Lagrangian function.

Then the following quadratic programming problem has to be solved [2]:

$$\min \frac{1}{2} d^T B_k d + \nabla f(x_k)^T d \tag{2.16.4}$$

$\boldsymbol{d} \in \mathbf{IR}^{\boldsymbol{n}} : \nabla \boldsymbol{g_j}(\boldsymbol{x_k})^{\boldsymbol{T}} \boldsymbol{d} + \boldsymbol{g_j}(\boldsymbol{x_k}) = 0, \boldsymbol{j} = 1, \ldots, \boldsymbol{m_e}$
$\nabla g_j(x_k)^T d + g_j(x_k) \geq 0, j = m_e, \ldots, m.$. Let $\mathbf{d}_k$ be the optimal solution and $u_{\boldsymbol{k}}$ the corresponding multiplier. A new itereate is obtained by [2]:

$$\begin{pmatrix} \mathrm{x}_{k+1} \\ \mathrm{v}_{k+1} \end{pmatrix} := \begin{pmatrix} \mathrm{x}_k \\ \mathrm{v}_k \end{pmatrix} + \alpha_k \begin{pmatrix} \mathrm{d}_k \\ \mathrm{u}_k - \mathrm{v}_k \end{pmatrix} \tag{2.16.5}$$

where $\alpha_k \in (0, 1]$ is a suitable steplength parameter.

An SQP method is identical to Newtons's method to solve the necessary optimality conditions, if B_k is the Hessian of the

Lagrangian function and if the startvalues are close to a solution.

If $d_k = 0$ is an optimal solution of (4) and u_k the corresponding multiplier vector, then $\mathbf{x}_k$ and u_k satisfy the necessary optimality conditions of (2.16.1).

Since the calculation of the Hessian of the Lagrangian function is very expensive regarding run time, the Hessian matrix is approximated by updating B_k by the BFGS quasi-Newton formula. The calculation of any new matrix B_{k+1} depends only on B_k and two vectors [2]:

$$q_k := \nabla_x L(x_{k+1}, u_k) - \nabla_x L(x_k, u_k) \tag{2.16.6}$$

$$w_k := x_{k+1} - x_k \tag{2.16.2}$$

$$B_{k+1} := \prod (B_k, q_k, w_k) \tag{2.16.7}$$

$$\prod (B, q, w) := B + \frac{qq^T}{q^T w} - \frac{Bww^T B}{w^T Bw} \tag{2.16.8}$$

The above formula yields a positive definite matrix B_{k+1} provided that B_k is positive definite and $\mathbf{q}_\mathbf{k}^\mathbf{T}\mathbf{w}_\mathbf{k} > 0$.

As already stated, the given optimization problem is not smooth. To avoid the direct calculation of the gradients the results calculated in the line search are approximated with a quadratic function. Since this function is differentiable, the gradients used in the SQP method could be calculated. The optimization of the gear shifting map does not include any constraints, but some boundaries for the parameter vector (discretization nodes) which are chosen according to the possible movement of the nodes.

The optimized shifting program can be defined and optimized in the unit for speed as well as in the unit for velocity. The units of the shifting program and the optimized shifting program influence each other. That means, if one of these programs is loaded with a different unit, also the other program gets this new unit.

If the optimized shifting program is defined in the unit for velocity, the Data Bus input 'Velocity' must be connected.

Kickdown Table

$\dot{\varphi}_{P,incr,KD}[n]$	Upshifting Speed at Kickdown dependent on the gear	rpm
$\dot{\varphi}_{P,decr,KD}[n]$	Downshifting Speed at Kickdown dependent on the gear	rpm

The Kickdown Table is used when the driver steps full on the acceleration pedal (load signal = 100 %). Instead of this criterion, the optional Data Bus input 'Kickdown Signal' can be used to control the kickdown event.

Velocities can be defined instead of speeds. In this case the Data Bus input 'Velocity' has to be connected.

Shifting Programs Advanced
Shifting Programs 1–5

$\dot{\varphi}_{P,adv,incr}[n, \alpha_{E,dk}]$ or $v_{P,adv,incr}[n, \alpha_{E,dk}]$	Upshifting Speed 1–5 (Velocity) dependent on the gear and the load signal	rpm or km/h
$\dot{\varphi}_{P,adv,decr}[n, \alpha_{E,dk}]$ or $v_{P,adv,decr}[n, \alpha_{E,dk}]$	Downshifting Speed 1–5 (Velocity) dependent on the gear and the load signal	rpm or km/h

Up to five shifting programs can be defined. With the Data Bus input 'Shifting Program Selector' (which provides a double value), interpolations between the shifting programs can be done.

Kickdown Tables 1–5

$\dot{\varphi}_{P,adv,incr,KD}[n]$.	Upshifting Speed at Kickdown dependent on the gear	rpm
$\dot{\varphi}_{P,adv,decr,KD}[n]$.	Downshifting Speed at Kickdown dependent on the gear	rpm

To each advanced Shifting Program an associated Kickdown Table can be defined. To do this, the properties switch 'Kickdown Table' must be activated.

Selection Button Data Sheet Selection

All 1,…,5

When this switch is set to 'all' and more than one shifting program is activated, the Data Bus input 'Shifting Program Selector' is used to determine the shifting program and Kickdown Table used for calculation. A constant program/kickdown table can be selected with the values 1–5.

Remark: The advanced shifting programs import gear shifting data generated by the task 'GSP Generation'

Shift Remaining Time

$t_{\mathrm{P,upShiftRemain}}[n]$	Remaining Time for Upshifting dependent on the gear	s
$t_{\mathrm{P,DownShiftRemain}}[n]$	Remaining Time for Downshifting dependent on the gear	s

When in the properties window the switch 'Shift Remaining Time' is activated, the remaining time for upshifting and downshifting for every gear can be defined. The remaining time is the minimal time after the shift decision, in which no further shifting is allowed.

Exception: a kickdown situation. In this case there is no remaining time.

2.16.3 Input and Output Variables

2.16.3.1 Data Input

$j_{\mathrm{P,act}}$	Current Gear	–
$\dot{\varphi}_{\mathrm{P,ref,act}}$	Speed	rad/s
$\alpha_{\mathrm{P,act}}$	Load Signal	–
$\mathrm{S}_{\mathrm{P,KD}}$	Kickdown Signal	–
$v_{\mathrm{P,act}}$	Velocity	m/s
$c_{\mathrm{P,sel}}$	Shifting Program Selector	–

2.16.3.2 Data Output

$j_{\mathrm{P,new}}$	Desired Gear	–
$\dot{\varphi}_{\mathrm{P,upshifting}}$	Speed Upshifting	rad/s
$\dot{\varphi}_{\mathrm{P,downshifting}}$	Speed Downshifting	rad/s

These channels with the actual speeds for up and downshifting are available for user-defined controls (in function component, Black Box, MATLAB® API, MATLAB® DLL).

For advanced control algorithms, for current load signal and gear, the gearbox program calculates upper and lower speed limits for shifting.

In order to ensure the existence of upper and lower speed limits, in the lowest gear, lower speed limit is calculated as (current speed—INFINITESPEED), and in the highest gear, upper speed limit is calculated as (current speed + INFINITESPEED).

INFINITESPEED is defined in the Cruise.ini file with the default value of 104.72 rad/s which equals 1000 rpm.

2.16.4 Computation Variables

N_G	Number of gears	–

2.16.5 Equation System

Gear shifting to the next or next lowest gear will be done according to the gear shifting criteria by using the defined maps.

2.17 CVT Control (H)

The CVT Control is an easy way to pretend a target transmission considering the velocity and the engine load. In addition there is a possibility of controlling a clutch. This clutch is simply added to the model but it is not necessary [1].

2.17.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Control Value
Transmission Ratio
Input Speed
Input Speed (ECO)
In this case the CVT is controlled by definition of Desired Transmission Ratio depending on velocity and load signal.

Selection Button Control Value
Transmission Ratio
Input Speed
Input Speed (ECO)
In this case the CVT is controlled by definition of Desired Input Speed depending on velocity and load signal. With this information the actual transmission ratio is then calculated. When using this option, the Data Bus input channel 'Input Speed' has to be connected.

Selection Button Control Value

Transmission Ratio

Input Speed

Input Speed (ECO)

In this case a separate map can be activated to import data generated by the task 'GSP Generation'.

2.17.2 User-Defined Variables

Time Constant Load Signal

t_{load}	Time constant Load Signal	s

Here the time constant of the PT1-retarding element for the load signal can be defined.

Time Constant Velocity

t_v	Time constant Velocity	s

Here the time constant of the PT1-retarding element for the velocity can be defined.

Desired Transmission Ratio

$i_{H,soll}\ (v_V,\ \alpha_{E,dk})$	Desired Transmission Ratio as a function of velocity and load signal	–

Here the demand transmission of the CVT gearbox can be defined as a function of the velocity and the load signal.

Desired Input Speed

$\dot{\varphi}_{H,soll}(v_V, \alpha_{E,dk})$	Desired Input Speed as a function of velocity and load signal	rad/s

Here the demand input speed of the CVT gearbox can be defined as a function of the velocity and the load signal.

To use this option, the Selection button 'Control Value' has to be set to 'Input Speed' and the Data Bus input channel 'Output Speed' has to be connected.

Desired Input Speed (ECO)

$\dot{\varphi}_{H,soll}(v_V, \alpha_{E,dk})$	Desired Input Speed as a function of velocity and load signal	rad/s

This map works just like the 'Desired Input Speed' map. To use it, the selection button 'Control Value' has to be set to 'Input Speed (ECO)' and the Data Bus input channel 'Output Speed' has to be connected.

Desired Clutch Release

$L_{\mathbf{H,soll}}\left(\dot{\varphi}, \alpha_{\mathbf{E,dk}}\right)$ or $L_{\mathbf{H,soll}}\left(v_{\mathbf{V}}, \alpha_{\mathbf{E,dk}}\right)$	Desired Clutch Release as a function of speed (or velocity) and load signal	%

The demand clutch release of the starting clutch can be defined as a function of the speed (or velocity) and the load signal.

Fast Linear Interpolation for CVT Control Maps
The interpolation in the maps of CVT control (e.g. interpolation of transmission ratio) is done by an alternative method which does not use the map preprocessing approximation to equidistant points.

This method is the default setting and can be changed in the 'Interpolation and Approximation' section in the 'Expert Mode' settings of the Project Settings (switch 'Fast Linear Interpolation for CVT-Control-Maps').

2.17.3 Input and Output Variables

2.17.3.1 Data Input

$\alpha_{\mathrm{H,act}}$	Load Signal	–
$\dot{\varphi}_{\mathbf{H,ref,act}}$	Speed	rad/s
i_{H}	Current Transmission Ratio	–
V_{H}	Velocity	m/s
M_{H}	Torque	Nm
$\dot{\varphi}_{\mathbf{H,out,control}}$	Output Speed	rad/s

2.17.3.2 Data Output

$\dot{i}_{\mathrm{H,dem,act}}$	Desired Transmission Ratio	–
$L_{\mathrm{H,dem,act}}$	Desired Clutch Release	%

2.17.3.3 Equation System

The demanded transmission step is selected from the map for the current vehicle velocity and the throttle position.

The same thing is done for the new clutch release. Here, the reference speed and the throttle position are taken into consideration.

2.18 Anti-Slip Control (ASC)

The Anti-Slip Control checks the Force Transmission Factor (ratio between force that has to be transmitted and maximum transmittable force) of all connected wheels (driven wheels). If the force that has to be transmitted exceeds the adhesion limit, the load signal or the clutch release changes [1].

The Anti-Slip Control is only active when a model is calculated quasi-stationary in combination with special drive train configurations [1].

2.18.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

Switch Use for Simulation
If the ASC should be used for calculations in simulation mode this switch can be activated. In this case the parameters for the PID controller can be set.

2.18.2 User-Defined Variables

PID Controller

$P_{ASC,pro}$	Proportional Parameter	–
$P_{ASC,dif}$	Differential Parameter	s
$P_{ASC,int}$	Integral Parameter	1/s

Here the parameters for the PID controller can be defined. This controller is used for the controlling of the ASC.

2.18.3 Input and Output Variables

2.18.3.1 Data Input

$\alpha_{ASC,in}$	Load Signal	%
$S_{ASC,in}$	Clutch Release	–
$S_{ASC,i}$	Wheel slip of the ith connected wheel	–

A maximum of four wheels can be connected with the ASC.

2.18.3.2 Data Output

$\alpha_{ASC,out}$	Load Signal	%
$S_{ASC,out}$	Clutch Release	–

2.18.3.3 Equation System

At first, the wheel with the highest value for the load transmitting factor is selected (Fig. 2.19). If this value greater than 1, the Anti-Slip Control is activated $(z_{ASC} = -1)$ and the load position will be reduced as long as the wheels have slip conditions.

For the task Full Load Acceleration from rest, the value for the clutch release will be increased.

For the modification of the signals a PID controller is used. The parameter values have to be entered in the input dialog.

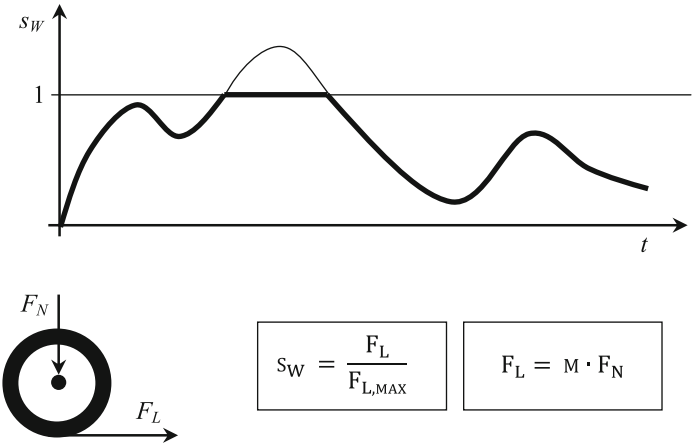


Fig. 2.19 Load transmitting factor [2]

2.19 PID Control (PID)

Combined with other signal processing components (e.g. 'function' component), the PID control may be used to build up more powerful control subsystems in AVL CRUISE. It basically supports two operation modes [1].

The first mode is the 'Standard PID Control' mode, using the difference between a desired value and an actual value' to generate an 'output value'. The second mode is the 'Advanced Signal Control with Limitation' mode, where an additional input 'Control Value' (typically 'Desired Clutch Release' signal from component 'Cockpit') is taken into account and added to the 'output value' [1].

In this mode, 'Output Value' may be used to limit 'Actual Value' from the lower side (as, e.g., wheel load signal) or from the upper side (as, e.g., vehicle acceleration). This mode may be used with caution for other signals, too. It is important that the 'Control Value' has a 'natural' limit of zero, as it is the case with 'Desired Clutch Release' [1].

2.19.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button PID Mode
Standard PID Control
Advanced Signal Control With Limitation
The functionality of a standard PID control is supported.

Selection Button PID Mode
Standard PID Control
Advanced Signal Control With Limitation
The second operation mode of the PID control is calculated.

Selection Button Actual Value Limitation
Lower Limit
Upper Limit
The actual value is limited from the lower side. This option is only available in the second operation mode of the PID control.

Selection Button Actual Value Limitation
Lower Limit
Upper Limit
The actual value is limited from the upper side. This option is only available in the second operation mode of the PID control.

Switch Fixed Desired Value
In this case the desired value is defined by a constant value. This switch can only be chosen in the 'Simple PID Control' mode.

Switch Output Value Limitation
If this switch is activated, the output value can be limited by defining of a minimum and a maximum value.

2.19.2 User-Defined Variables

$C_{PID,P}$	Proportional Parameter	–
$C_{PID,P}$	Differential Parameter	s
$C_{PID,I}$	Integral Parameter	1/s

The PID parameters should be defined.

Actual Value Limitation

$C_{PID,act,min}$	Minimum	–

If the selection button **Actual Value Limitation** is set to *Lower Limit,* the possible minimum of the actual value has to be defined.

$C_{PID,act,max}$	Maximum	–

If the selection button **Actual Value Limitation** is set to *Upper Limit,* the possible minimum of the actual value has to be defined.

Fixed Desired Value

$C_{PID,fixed}$	Fixed Value	–

If the switch **Fixed Desired Value** is chosen, the desired constant has to be defined.

Output Value Limitation

$C_{PID,out,min}$	Minimum	–
$C_{PID,out,max}$	Maximum	–

If the switch **Output Value Limitation** is chosen, the possible minimum and maximum of the output value are defined here.

2.19.3 Input and Output Variables

2.19.3.1 Data Input

$C_{\text{PID,act}}$	Actual Value	–
$C_{\text{PID,desired}}$	Desired Value	–
$C_{\text{PID,control}}$	Control Value	–

2.19.3.2 Data Output

$C_{\text{PID,out}}$	Output Value	–

The output value is sent to the Data Bus and can be used by other components.

2.19.4 Equation System

2.19.4.1 Calculation of Delta Signal and PID output

The difference between target value and actual value is calculated by [2]:

$$\Delta C = C_{\text{PID,desired}} - C_{\text{PID,act}} \tag{2.19.1}$$

If there is a limitation of the actual value by definition of a lower limit, the sign of ΔC is changed.

The controller output is defined by [2]:

$$C_{\text{PID,out}} = C_{\text{PID,P}} \cdot \Delta C + C_{\text{PID,I}} \cdot \int_0^t (\Delta C)(\tau)\mathrm{d}\tau + C_{\text{PID,D}} \cdot \frac{\mathrm{d}(\Delta C)}{\mathrm{d}t} \tag{2.19.2}$$

In the 2nd mode ('Advanced Signal Control With Limitation'), the entire controller output is calculated by [2]:

$$C_{\text{PID,entireOut}} = C_{\text{PID,out}} + C_{\text{PID,control}} \tag{2.19.3}$$

2.19.4.2 Output Value Limitation

$C_{\text{PID,entireOut}}$ is limited by $C_{\text{PID,act,min}}$ and $C_{\text{PID,act,max}}$.

Additionally, in the following 2 cases:

1. $C_{PID,out,old} \leq C_{PID,act,min}$ **and** $C_{PID,out} < 0$
2. $C_{PID,out,old} \geq C_{PID,act,max}$ **and** $C_{PID,out} > 0$,

$C_{PID,out}$ is set to 0.

2.19.4.3 Reset of Integral

If the PID Control is in 2nd mode ('Advanced Signal Control With Limitation'), $\Delta C < 0$ and $C_{PID,out} = 0$, the control is set to 'neutral' position, that means ΔC, ΔC_{old} and the
Integral are set to 0.

2.20 Brake (B)

The brake component is described by brake data and dimensions. It is possible to define drum brakes as well as disc brakes. The retarder is used for heavy vehicles and is described below.

The braking torque is computed considering the braking dimensions and the input brake pressure. This brake pressure can come from the cockpit component or brake control [1].

If the vehicle is standing still, the degrees of freedom will be reduced as this reduces the calculation time also. This reduction is done in a way that the equation system is switched if a small velocity threshold is reached. In this case movement is suppressed. At the same time it is always checked if the instantaneous compulsive force is smaller than the braking torque. If this condition is no longer true the brake is given free again [1].

2.20.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

Switch Dynamic Mode
This switch is activated by default. The brake calculation always stays dynamic and never switches to a kinematic connection. Deactivation might be done for modeling a sticking brake in kinematic mode.

Selection Button Control Variable
Brake Pressure
Braking Torque

In this case the brake is controlled by the brake pressure which has to be supplied via Data Bus input 'Brake Pressure'.

Selection Button Control Variable

Brake Pressure

Braking Torque

In this case the engine is controlled by the desired braking torque value which has to come from the connected Data Bus input 'Braking Torque.'

2.20.2 User-Defined Variables

A_B	Brake Piston Surface	m^2

The brake piston surface is the area of the hydraulic cylinder. Multiplied with the brake pressure and the efficiency, it gives the axial brake force.

μ_B	Friction Coefficient	–

The friction coefficient is between the brake drum, respectively the friction disc and the brake shoes.

c_B	Specific Brake Factor (Disc brake $c_B = 1$; Drum brake $c_B > 1$)	–

The specific brake factor is a factor that depends on the design of the brake. For disc brakes it is always one, for drum brakes it is usually larger than 1.

r_B	Effective Friction Radius	m

The effective friction radius is the radius where the braking force applies.

η_B	Efficiency	–

The efficiency considers the effects of the conversion of the hydraulic into the mechanical part of the brake (Fig. 2.20).

Θ_B	Inertia Moment	kg m^2

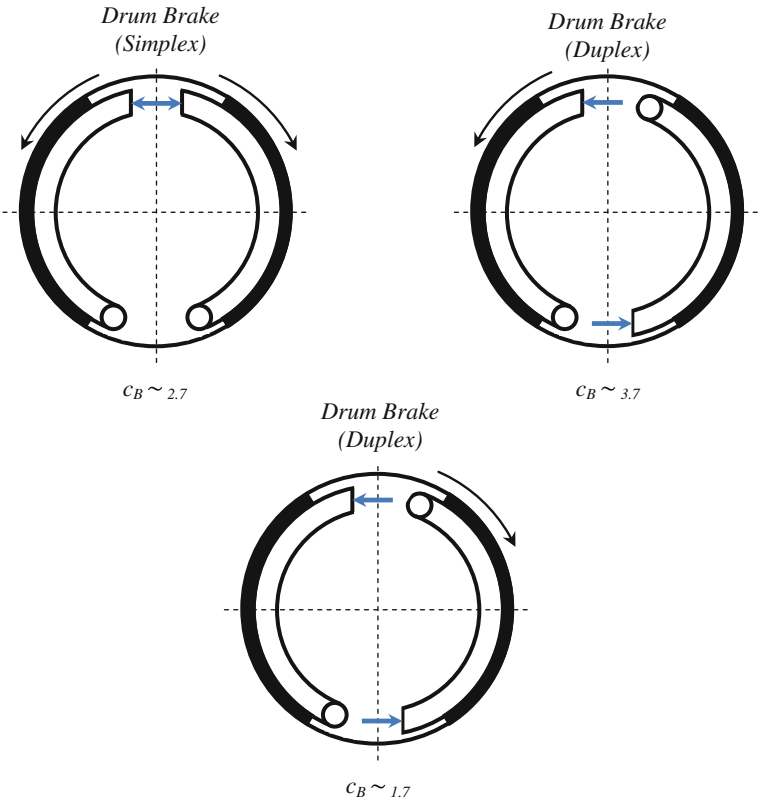


Fig. 2.20 Specific brake factors for different brake types [2]

2.20.3 Input and Output Variables

2.20.3.1 Mechanical Connection

$\dot{\varphi}_B$	Angular velocity of the brake	rad/s
$\ddot{\varphi}_B$	Angular acceleration of the brake	rad/s^2
M_B	Braking torque	Nm

2.20.3.2 Data Input

P_B	Brake Pressure	Pa
M_B	Braking Torque	Nm

2.20.3.3 Data Output

$\dot{\varphi}_{\mathrm{B}}$	Speed	rad/s
M_{B}	Braking Torque	Nm
P_{B}	Power	W

2.20.3.4 Equation System

The instantaneous braking torque will be computed as follows [2]:

$$\boldsymbol{M_{\mathrm{B}}} = 2 \cdot \boldsymbol{p_{\mathrm{B}}} \cdot \boldsymbol{A_{\mathrm{B}}} \cdot \eta_{\mathrm{B}} \cdot \mu_{\mathrm{B}} \cdot \boldsymbol{r_{\mathrm{B}}} \cdot \boldsymbol{c_{\mathrm{B}}} \tag{2.20.1}$$

2.21 Cockpit (CO)

The cockpit links the driver and the vehicle. In this component, there are only connections made via the Data Bus. On one hand, the driver receives information such as the vehicle velocity and the vehicle acceleration. On the other hand, information about of the driver, such as the pedal positions, are delivered to other components. The pedal positions (e.g. clutch pedal position) are transferred into corresponding indicators (e.g.. clutch release) via the pedal characteristics (e.g. clutch pedal characteristic) [1].

2.21.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

Switch Actual Distance and Velocity From Data Bus
The actual distance and velocity are taken from the Data Bus channels ‘Actual Distance extern’ and ‘Actual Velocity extern’.

Switch Desired Velocity From Data Bus
When using AVL CRUISE as a dynamic linked library (CruiseNT.dll) with the component ‘Interface’, the internal driver can control the velocity which is preset over the Data Bus channel ‘Desired Velocity extern’.

It is important to connect the channel on the Data Bus system with an external time depending signal. The driver will follow this desired velocity in an appropriate range. Note that there must be an adapted profile. e.g.. gear shifting in the task Cycle Run.

2.21.2 User-Defined Variables

$Z_{CO,gear}$	Switch for manual or automatic gear shifting	–

The switch is used for the Calculation Tasks, so that the calculation knows if the gear shifting process should be controlled by the driver (manual) or the gearbox control.

$N_{CO,G,for}$	Number of Gears (forward)	–
$N_{CO,G,rev}$	Number of Gears (reverse)	–

This is used to indicate to the driver how many gears the gearbox contains, i.e., if there is still another gear for upshifting or not.

$F_{CO,brake,max}$	Maximum Brake Force	N

The maximum brake pedal force is needed for the calculation of the brake pedal position. Output of the driver component is the brake pedal force. This brake pedal force divided by the maximum brake pedal force is the brake pedal position.

It is also possible to define a maximum brake force in the component driver. With this maximum brake force, the behavior of a driver can be considered. You can have a driver who is stepping with a maximum of e.g. 100 N on the brake pedal (defined in the driver component) and in the cockpit the maximum brake pedal force is defined as 200 N. That means that the driver can have a maximum of 50 % of the brake pedal position (100 N divided by 200 N). Thus, he has a lower brake pressure and a longer brake distance.

$N_{CO,R}$	Number of Retarder Steps	–

This is used to give the driver the information how many retarder steps the retarder is containing, i.e., if there is still another step with a higher braking torque or not.

Acceleration Pedal Characteristic

$\alpha_{CO,th}$ (L_{dk})	Load signal as function of the Acceleration Pedal Travel	%

Clutch Pedal Characteristic

$Z_{CO,clutch}$ (L_C)	Clutch Release as a function of the Clutch Pedal Travel	%

Brake Pedal Characteristic

$p_{CO,brake}$ (L_{Br})	Brake Pressure as a function of the Specific Brake Pedal Force	bar

The characteristics of the brake pedal, the clutch pedal, and the acceleration pedal can be defined. It is possible to define an idle path or a special shape of the characteristic.

2.21.3 Input and Output Variables

2.21.3.1 Data Input

$\dot{\boldsymbol{\varphi}}_{\mathbf{CO}}$	Speed	rad/s
$Z_{\mathrm{CO,cont,in}}$ (i)	Operation Control 0–4	–
$j_{\mathrm{CO,act}}$	Gear Indicator	–
$j_{\mathrm{CO,target}}$	Target Gear	–
$\dot{\boldsymbol{\varphi}}_{\mathbf{CO,measure_1}}$	Measuring Speed 1	rad/s
$\dot{\boldsymbol{\varphi}}_{\mathbf{CO,measure_2}}$	Measuring Speed 2	rad/s
s_{extern}	Actual Distance extern	m
v_{extern}	Actual Velocity extern	m/s
v_{extern}	Desired Velocity extern	m/s

2.21.3.2 Data Output

$Z_{\mathrm{CO,acc,out}}$	Load Signal	–
$p_{\mathrm{CO,br,out}}$	Brake Pressure	bar
$Z_{\mathrm{CO,cl,out}}$	Desired Clutch Release	%
$N_{\mathrm{CO,G,out}}$	Desired Gear	–
$Z_{\mathrm{CO,sh,up,out}}$	Gear Selection Upshifting	–
$Z_{\mathrm{CO,sh,dn,out}}$	Gear Selection Downshifting	–
$Z_{\mathrm{CO,sh,sel}}$	Control Lever	–
$N_{\mathrm{CO,ret,out}}$	Retarder Step	–
$Z_{\mathrm{CO,br,sigl}}$	Brake Light Switch	–
$Z_{\mathrm{CO,rev,sig}}$	Reverse Gear Switch	–
$\dot{\boldsymbol{\varphi}}_{\mathbf{CO,out}}$	Speed	rad/s
$v_{\mathrm{CO,out}}$	Velocity	m/s
$a_{\mathrm{CO,out}}$	Acceleration	$\mathrm{m/s^2}$
$t_{\mathrm{CO,out}}$	Real Time	s
$s_{\mathrm{CO,out}}$	Distance	m
$Z_{\mathrm{CO,start,out}}$	Start Switch	–
$T_{\mathrm{CO,ambient}}$	Ambient Temperature	°C
$Z_{\mathrm{CO,cont,out}}$	Operation Control	–

(continued)

$Z_{CO,sig,out}(i)$	Course Signal 1–3	–
$Z_{CO,kick,out}$	Kickdown Signal	–
$\dot{\varphi}_{CO,measure_1}$	Measuring Speed 1	rad/s
$\dot{\varphi}_{CO,measure_2}$	Measuring Speed 2	rad/s
$Z_{CO,Jake\ Brake}$	Jake Brake Activation	–
$v_{CO,desired}$	Desired Velocity from Profile	m/s
$v_{CO,max}$	Course Speed Limit	m/s
$j_{CO,profile}$	Desired Gear from Profile	–
$N_{CO,task}$	Type of Task	–

2.21.3.3 Equation System

In the module cockpit, switch, and selection functions were done. Input data were transformed depending to the calculation settings and maps.

After that the changed values were put onto the output channels.

2.22 Exhaust System (EX)

Exhaust systems consider the effects of the catalytic converter and soot filter on the raw emissions of the engine. Starting with the temperature of the catalytic converter, factors for the conversion will be computed for the single emissions components on the basis of the temperature-dependent maps [1].

2.22.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

Selection Button Temperature
Temperature calculated
Temperature from Data Bus
Calculation of temperature by using the thermal model

Selection Button Temperature
Temperature calculated
Temperature from Data Bus
The temperature is calculated by an external simulation tool and is transferred into the catalyst component via Data Bus.

2.22.2 User-Defined Variables

$Z_{EX,loss}$	Heat Loss Coefficient	–

The heat loss coefficient is for determining which amount of the exhaust energy the engine has delivered reaches the exhaust system and which amount is lost between the engine and the exhaust system to the environment.

The heat loss coefficient is the percentage of the exhaust energy delivered by the engine which reaches the exhaust system.

m_{EX}	Weight of Catalytic Converter	kg

This is the weight of the catalytic converter. This weight is needed for the calculation of the temperature of the catalytic converter and as consequence the efficiency of the emission conversion (Fig. 2.21).

$C_{p,EX}$	Specific Heat Capacity Cat	J/kg

This is the specific heat capacity of the catalytic converter which is needed for the calculation of the temperature of the catalytic converter.

$A_{EX,ref}$	Reference Area Cat/Air	m^2

The reference area of the exhaust system is the outside surface area of the catalytic converter. It is needed for the calculation of the heat transfer between the catalytic converter and the ambient air.

$\alpha_{EX,air}$	Heat Transfer Coefficient Cat/Air	W/m^2 K

This is the coefficient for the heat transfer between the catalytic converter and the ambient air. With this heat transfer, the energy lost to the environment can be determined.

$T_{EX,op}$	Operating Temperature Cat	°C

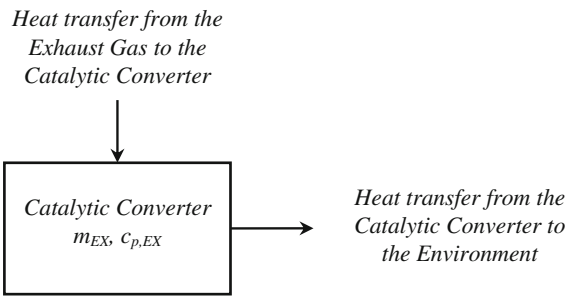


Fig. 2.21 Thermal balance in the exhaust system [2]

The operating temperature is needed for a calculation with hot start. If the hot start is chosen, the temperature of the catalytic converter at the beginning of the calculation is equal to the operating temperature. If cold start is chosen, the temperature of the catalytic converter at the beginning of the calculation is equal to the ambient temperature.

Conversion Efficiency

$\eta_{EX,NOx}(T_{EX})$	NO_x—Conversion Efficiency	–
$\eta_{EX,CO}(T_{EX})$	CO—Conversion Efficiency	–
$\eta_{EX,HC}(T_{EX})$	HC—Conversion Efficiency	–
$\eta_{EX,Soot}(T_{EX})$	Soot—Conversion Efficiency	–

In these tables, the conversion efficiencies of the different emissions can be defined dependent on the actual temperature of the catalytic converter.

Heat Transfer Gas/Cat

$\alpha_{EX,gas}(T_{EX})$	Heat-up Proportion of Exhaust Gas Energy	–

This is the proportion of the heat of the exhaust gas which is transferred to the exhaust system.

2.22.3 Input and Output Variables

2.22.3.1 Data Input

$T_{EZ,ext,in}$	Temperature External	K

2.22.3.2 Data Output

$P_{EX,out}$	Residual Energy	W
$e_{EX,NOx,out}$	Rest Emissions NO_X	kg/s
$e_{EX,CO,out}$	Rest Emissions CO	kg/s
$e_{EX,HC,out}$	Rest Emissions HC	kg/s
$e_{EX,SOOT,out}$	Rest Emissions SOOT	kg/s
T_{EX}	Temperature	°C

2.22.4 Computation Variables

Q_{EX}	Heat capacity of the exhaust system	J/K
$\eta_{EX,\ \ldots,act}$	Actual reduction rate	–

2.22.5 Equation System

In relation to the entered exhaust energy P_{EX}, the heat transmitting conditions, the heat capacity of the exhaust system, and the temperature of the exhaust system T_{EX} are calculated.

In the next calculation step, the efficiency values $\eta_{EX,act}$ concerning T_{EX} are evaluated out of the maps.

The rest emissions are calculated with the following formula [2]

$$e_{EX,out} = e_{EX,\ldots,in} \cdot \left(1 - \eta_{EX,\ldots,act}\right) \tag{2.22.1}$$

2.23 MATLAB®/Simulink™ (ml)

The interface to MATLAB® integrates controllers and also mechanical elements, such as special drives created by MATLAB®/Simulink™, into the computational model of AVL CRUISE. An element created and parameterized under Simulink™ will be compiled to a so-called "Dynamic Link Library" (DLL) under Windows. These files will be integrated into AVL CRUISE. The advantage of this procedure is that AVL CRUISE itself does not need to be recompiled if MATLAB®/Simulink™ modules are integrated [1].

The input and output variables will be transferred by means of imports and outports. These ports create the interface to the MATLAB® module and are available at the AVL CRUISE Data Bus. As two simulations, i.e., those of AVL CRUISE and MATLAB®/Simulink™, take place at the same time in this case, the integration steps of the two programs will have to be harmonized by a suitable selection of the step width [1].

2.23.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

2.23.2 User-Defined Variables

$C_{ML,Lib}$	Name of MATLAB®-Library (can be selected in a file selection dialog)	–

2.23.3 Input and Output Variables

2.23.3.1 Data Input

$X_{ML,in}(i)$	Inport 0–98	–

2.23.3.2 Data Output

$X_{ML,out}(i)$	Outport 0–98	–

2.23.3.3 Equation System

The input values are transferred to the MATLAB® function. From the module, the results are received and input to the output channels.

Refer to the interfaces manual for more information.

2.24 Function (FU)

The component Function can be used for calculating with user-defined functions.

There are two possibilities to define the function:

(a) Function definition in RPN-notation style (Reverse Polish Notation, UPN, Postfix Notation, Stack Logic). No need for programming, the component has a user-friendly selection table. Only one function output y can be defined.

(b) Programming in C code. Up to 99 function outputs can be defined.
Up to 99 input values can be read through the Data Bus. The values are the function arguments, together with up to 10 constants defined by the user. Those arguments must be connected to form the function term by using operators which can be selected from a selection menu. Also the most important physical constants (e.g., n) are in this menu, which can be selected as additional function arguments. After the function value has been calculated, it can be used on the Data Bus as an output value. When defining the function in C code, it is possible to deliver values up to 99 function outputs [1].

2.24.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Formula Mode
RPN-Formula
C-Function
In this case the formula definition has to be done by the so-called Reverse Polish Notation (UPN, postfix notation, stack logic).

Selection Button Formula Mode
RPN-Formula
C-Function
The function has to be defined in C code.

2.24.2 User-Defined Variables

RPN-Formula Mode
This mode is active if the selection button 'Formula Mode' is set to RPN-formula.

$Z_{FU}(i)$	User-defined Constants (maximum 10)	–

Up to 10 constants can be defined to be used in the function as arguments (upper case letters A, B, C, D, E, F, G, H, K, M).

$Z_{FU,pi}$	Physical Constant PI (π)	–
$Z_{FU,acc}$	Physical Constant 9.81	kg m/s^2

The most important pre-defined constants can be selected from a selection menu and used as function arguments.

t_{FU}	Variable 'realTime'	–

In every time step this variable has the same value as the Data Bus output channel 'Real Time' of component cockpit. It can be used in System Analysis Mode (SAM) in models without a cockpit.

$op_{FU,arith}(j)$	Arithmetical Operators: +, −, −, /	–
$op_{FU,arith}(j)$	Operators: Derivation (2 arguments), Integration (3 arguments; the 3rd argument represents the Reset signal, see below)	–
$op_{FU,arith}(j)$	Operators: Time Derivation (1 argument), Time Integration (2 arguments; the 2rd argument represents the Reset signal, see below)	–
$op_{FU,unary}(j)$	Operators: abs, sgn, high, low, max, min, 1/x, **, +/−	–
$op_{FU,unary}(j)$	Operators: rad > deg, deg > rad	–
$op_{FU,trig}(j)$	Operators: sin, cos, tan, arcsin, arccos, arctan	–
$op_{FU,hyp}(j)$	Operators: sinh, cosh, tanh, arsinh, arcosh, artanh	–
$op_{FU,log}(j)$	Operators: ln, exp	–
$op_{FU,logical}(j)$	Operators: NOT, AND, OR, <=, >=, <, >, ==, !=	–
?	Space Symbol	–
ENTER	End Mark of the function definition	–

The operators are selected from a selection menu. They form a function term with the constants and input values from the Data Bus as arguments. The function definition format is the so-called Reverse Polish Notation (UPN, postfix notation, stack logic), i.e., the term “A + a[0] =” is written as “A a[0] + ENTER”. The definition is done in a table and should be completed by typing Enter.

Click on the **Function Preview** button to open a window showing the function term converted into the “normal” prefix notation. Additionally, there is a copy button so that the user can copy this prefix term and paste it for example into the comment line.

C-Function Mode

This mode is active if the selection button ‘Formula Mode’ is set to C-Function.

$Z_{FU,C\text{-}Function}$	Function String	–

The function is written in C code, e.g.

‘y[0] = sin(2*a[0])/pow(a[1],1.5)—2.3’

Following contents are allowed (besides the input channels: a[0], a[1], …, a [98]):

$Z_{FU,C,Num}$	Numerical Constants	–

Free user-defined, e.g. 1, 3.14, 0.05

User-defined constants A, B, C like in the RPN-mode can be defined in C code as variables.

t_{FU}	Variable ‘realTime’	–

This is a pre-defined variable of type ‘double’ which can be used in the C code without a declaration. In every time step this variable has the same value as the Data Bus output channel ‘Real Time’ of component cockpit. It can be used in System Analysis Mode (SAM) in models without a cockpit.

Additionally, most of the ANSI C operators and statements can be used, e.g., the if-then statement.

Up to 99 Data Bus output variables y[0], y[1], …, y[98] can be delivered with output values.

2.24.3 Input and Output Variables

2.24.3.1 Data Input

$X_{FU,in}(i)$	Input Channels a[0], a[1], …, a[98]	–

Up to 99 values can be read from the Data Bus and used as function arguments (for RPN- mode only the first 20).

2.24.3.2 Data Output

$X_{FU,out}$	Output Channels y[0], y[1], …, y[98] (for RPN-mode only y)	–

The function values are sent to the Data Bus and can be used by other components. When defining the function in RPN-Formula mode, only the output y[0] can be used.

2.24.4 Equation System

The user-defined constants and the input values are transferred to the function which calculates the output values by using the formula that has been defined by the user in a table, or by using the user-defined C-function code. The output value(s) can be used by other components through the Data Bus.

Example

The input value a[0] should be multiplied by 9.81. The result should be multiplied by the factor 0.92 which has been defined as a constant (B).

In the parameter field the letter B is assigned the value 0.92. The function is defined in the formula table as follows:

B:= 0.92

Position	Y=
1	a[0]
2	9.81
3	*
4	B
5	*
6	ENTER

The expressions of the table are selected in a certain selection menu. At the end of the table ENTER should always be written.

Derivation
This operation has 2 arguments. For example, the following input table means that the signal of Data Bus input a[0] should be differentiated by the signal of Data Bus input a[1].

Position	y=
1	a[0]
2	a[1]
3	Derivation
4	ENTER

Integration
This operation has 3 arguments:

Position	y=
1	a[0]
2	a[1]
3	a[2]
4	Integration
5	ENTER

The above input table means that the signal of Data Bus input a[0] should be integrated by the signal of Data Bus input a[1], whereas Data Bus signal a[4] represents the reset signal.

The meaning of the reset signal is as follows:

Value	Action
>0	“normal” summation
0	Reset; integration output is set to 0 and stays 0 as long as the reset value is <=0
<0	No further summation

The trapezoid method is used as integration method.

Time Derivation, Time Integration
These operations are similar to derivation/integration, except that they have one argument less.

Their first argument is not differentiated/integrated by a second argument which can be chosen by using the Data Bus, but always by the (internal) simulation time.

2.25 Constants (CN)

In the Constants component the user can define up to 99 constant values which can be used by other components through the Data Bus. The values can be of type integer, double or string [1].

2.25.1 Properties

Switch Output
If this switch is activated a result output for this component is made.

2.25.2 User-Defined Variables

$Z_{CN}(i)$	User-defined Constants (maximum 99)	–

Up to 99 constants can be defined which can be used by other components via Data Bus. Every constant requires the definition of the Data Bus channel number, a comment, the constant value, the unit and the data type. Data type can be of integer, double or string.

In the case of a string constant, the unit definition is not used in calculation. The Data Bus transfers the pointer (address) of the string.

2.25.3 Input and Output Variables

2.25.3.1 Data Output

$Z_{CN,out}(i)$	Constant Outputs (maximum 99)	–

The constant output values are sent to the Data Bus and can be used by other components.

2.26 Monitor

The monitor can be introduced if the calculation run must be detected. It is possible to show some results of the calculation while the calculation is running. This is done via the online-monitor [1].

It is possible to connect up to ten input channels of the monitor to output channels of different components that are available at the AVL CRUISE Data Bus.

Currently, the output in the online-monitor is only available in the form of tables [1].

2.26.1 Properties

Switch Output
A result output for this component is made if this switch is activated.

2.26.2 Input and Output Variables

2.26.2.1 Data Input

$X_{\mathrm{Mon,in}}(i)$	Input 0–9	–

These input values can be read in via the Data Bus. During the calculation, they were written on the online-monitor for each time step.

2.27 Wheel/Tire (W)

The wheels and tires link the vehicle to the road. The component wheel allows to consider many influencing variables and their effect on the rolling state.

The moment of rolling drag can be computed on the basis of the wheel load, the corrected dynamic rolling radius, and the coefficient of rolling drag [1].

The longitudinal tire force (circumferential force) results from the friction coefficient, the wheel load as well as from the wheel load factor and the slip factor. It is possible to define variable friction coefficients along the driving profile when different road conditions are considered [1].

The wheel component also includes a detailed rolling resistance furnished by Michelin. This model describes the rolling resistance of the tire depending on the tire inflation pressure, load, translation speed, the ambient temperature and the time [1].

2.27.1 Properties

Switch Variation
The Wheel can be given free for variation with this switch. The setup of the variation parameters is done in the folder.

Switch Output
If this switch is activated a result output for this component is made.

Selection Button Dynamic Rolling Radius
Constant Value
From Characteristic
In this case the input constant value is used for the dynamic rolling radius.

Selection Button Dynamic Rolling Radius
Constant Value
From Characteristic
In this case the dynamic rolling radius is interpolated out of the characteristic.

Selection Button Wheel Slip
deactivated
Function
Function with Limit
Map
Map with Limit
In this case no consideration of the wheel slip in the calculation is possible.

Selection Button Wheel Slip
deactivated
Function
Function with Limit
Map
Map with Limit
Here the definition of the wheel slip is done by the characteristics "Maximum in the Slip Characteristic" and "Asymptote in the slip characteristic." If **Function with Limit** is selected the maximum slip is limited with a slip which is slightly higher than the maximum value from the slip characteristic.

This limitation is also used for **Function without limitation** for all stationary calculations (Climbing Performance, Full Load Acceleration/Acceleration in all Gears, Maximum Traction Force). This is done to avoid instabilities in the calculation and therefore results which can be misunderstood.

Selection Button Wheel Slip
deactivated
Function
Function with Limit
Map
Map with Limit

Here the specific traction (as percentage of the wheel load) is defined as function of the wheel slip and the friction coefficient of the road. If **Map with Limit** is selected the maximum slip is limited with a slip which is slightly higher than the maximum value from the traction map.

This limitation is also used for **Map without limitation** for all stationary calculations (Climbing Performance, Full Load Acceleration/Acceleration in all Gears, Maximum Traction Force). This is done to avoid instabilities in the calculation and therefore results which can be misunderstood.

Switch Rolling Resistance Model
If this switch is activated, the rolling resistance is calculated by a detailed resistance model.

Switch Rolling Resistance
wheel load dependent
wheel pressure dependent
velocity dependent
temperature dependent
With these switches the input of the rolling resistance can be defined. It is possible to activate more than one influence. All activated rolling resistances are added to the overall rolling resistance. These switches can only be activated if the Switch **Rolling Resistance Model** is deactivated.

Selection Button Dimensions
calculated
defined
In this case the tire diameter and the surface area are calculated with the input data of tire section width, tire aspect ratio and tire seat diameter.

Selection Button Dimensions
calculated
defined
In this case the tire diameter and the surface area are defined by the user.

Selection Button Wheel Location
Vehicle: Front Left
Vehicle: Rear Left
Vehicle: Rear Right
Vehicle: Front Right
Trailer: Left
Trailer: Right
Two Axle Trailer: Front Left
Two Axle Trailer: Rear Left
Two Axle Trailer: Rear Right
Two Axle Trailer: Front Right
With this selection button the location can be defined where this wheel is located on the vehicle or the trailer.

2.27.2 User-Defined Variables

θ_W	Inertia Moment of the Wheel	kg m^2

Wheel Slip

$\mu_{W,tire}$	Friction Coefficient of Tire	–

The friction coefficient of the tire depends on the material used in the tire. With this friction coefficient it is possible to consider the effects of different wheels on the behavior of the vehicle.

$F_{W,s,norm}$	Reference Wheel Load	N

The curves for the maximum slip in the slip curve and the transmission ratio at infinite slip are measured at the reference wheel load.

The calculation of the longitudinal force is done like follows [2]:

$$F_L = \mu_{Road} \cdot \mu_{W,Tire} \cdot c_S \cdot c_F \cdot F_{W,s} \tag{2.27.1}$$

F_L Longitudinal force
μ_{Road} Friction Coefficient of the road
c_S Slip Correction Factor
c_F Wheel Load Correction Factor
$F_{W,s}$ Wheel Load

$c_{W,s,F}$	Wheel Load Correction Coefficient	–

For the real wheel load is never the reference wheel load the longitudinal force has to be corrected with the wheel load correction factor (c_F). For this case the correction coefficient is used. It determines the gradient of the curve (refer to Fig. 2.22; the gradient is $-\frac{c_{W,S,F}}{F_{W,S,norm}}$)Although the gradient is normally negative, a positive correction coefficient has to be entered in the input field [2].

$$c_F = 1 - \frac{F_{W,act} - F_{W,S,norm}}{F_{W,S,norm}} \cdot c_{W,S,F} \tag{2.27.2}$$

$F_{W,act}$ actual wheel load

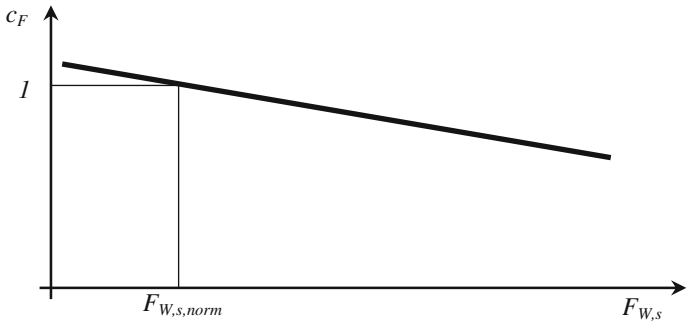


Fig. 2.22 Wheel load correction factor [2]

Rolling Radius

Static Rolling Radius

$r_{W,stat}$	Static Rolling Radius	mm

The static rolling radius is the distance between the center of the wheel and the road surface for the loaded vehicle but without moving.

The dynamic rolling radius is the distance between the center of the wheel and the road surface for the loaded vehicle with moving. The dynamic rolling radius is usually a little bit bigger than the static rolling radius.

Dynamic Rolling Radius (Constant)

$r_{W,dyn}$	Dynamic Rolling Radius	mm

The constant value is used when the selection button **Dynamic rolling radius** is set to constant value.

Dynamic Rolling Radius (Characteristic)

$r_{W,dyn}(v_V)$	Dynamic Rolling Radius	mm

Here the dynamic rolling radius can be defined as function of the velocity. This characteristic is active when the selection button *Dynamic rolling radius* is set to "from characteristic."

Slip Curve

Maximum in the Slip Characteristic

$s_{W,grenz}(\mu_{U,road})$	Slip at Maximum Traction	%

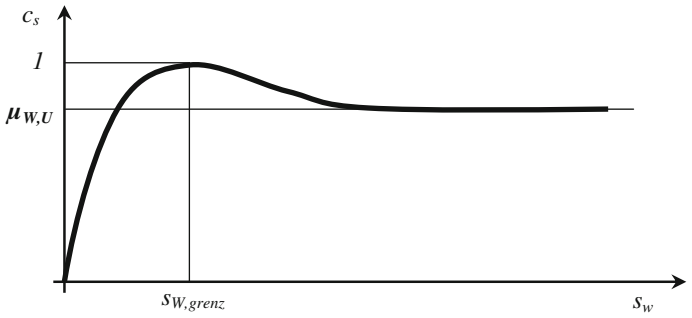


Fig. 2.23 Slip correction factor [2]

Asymptote of Slip Characteristic

$\mu_{W,U}(\mu_{U,road})$	Specific Traction at Infinite Slip	–

The slip at maximum traction is together with the specific traction at infinite slip the Characteristic Values for the slip correction factor (refer to Fig. 2.23). The slip correction factor depends on the friction coefficient of the road.

Traction Map

$\mu_{W,U}(s_W,\mu_{U,road})$	Specific Traction	%

This is a second possibility for the description of the wheel slip.

Rolling Resistance Factor

The rolling resistance is given in %, i.e., the rolling resistance force is calculated with [2]:

$$F_{W,r} = c_{W,r} \cdot F_{W,s} \tag{2.27.3}$$

$F_{W,r}$ Rolling Resistance Force

$c_{W,r,load}$	Rolling Resistance wheel load dependent	%

This part of the rolling resistance depends on the wheel load.

$c_{W,r,pres}$	Rolling Resistance wheel pressure dependent	%
$p_{W,ref}$	Nominal wheel pressure	bar

This part of the rolling resistance is converted form the nominal wheel pressure to the actual wheel pressure.

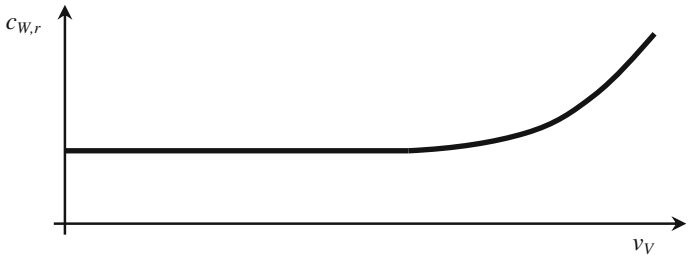


Fig. 2.24 Rolling resistance [2]

$c_{W,r}(v_V)$	Rolling Resistance as function of Vehicle Velocity	%

The rolling resistance depends on the vehicle velocity. It is nearly constant at lower velocities and increases when the velocity is getting higher. The velocity where the rolling resistance starts to increase depends on the design of the tire (refer to Fig. 2.24).

$c_{W,r,temp}(T_U)$	Rolling Resistance temperature dependent	%

This part of the rolling resistance depends on the actual environment temperature.

In the case of cornering the rolling resistance increases. It is possible specify a proximity relationship between this increase and the actual side slip angle.

Transient Rolling Resistance

The following inputs are required when the switch **Rolling Resistance Model** is activated.

Specification of dimension:

W_W	Tire Section Width	mm

The Tire Section Width is the linear distance between the outside sidewalls of an inflated tire without any load (exclusive of protruding side ribs and decorations).

R_W	Tire Aspect ratio	%

The Tire Aspect Ratio is (Section Height).100/Section Width, whereas the Section Height is the distance from rim seat to outer thread surface of the unloaded tire.

$D_{W,seat}$	Tire Seat diameter	in

The tire seat diameter is the diameter of the rim seat supporting the tire bead.

$D_{W,design}$	Tire Design Diameter	m

The tire design diameter is the diameter of the inflated tire without any load.

A_W	Tire Surface Area	m^2

The surface area is the total external surface area of the tire.

Depending on the selection button dimensions, the tire section width, tire aspect ratio and tire seat diameter, or the tire design diameter and tire surface area have to be defined.

Measured data at ISO-test conditions:

$c_{W,roll,ISO}$	Rolling Resistance Coefficient	–
$p_{W,ISO}$	Tire Inflation Pressure	bar
$F_{W,ISO}$	Tire Load	N
$v_{W,ISO}$	Tire Velocity	m/s

The tire velocity is the tangential velocity of the tire.

$T_{W,ISO}$	Reference Temperature	C
$c_{W,conv,ISO}$	Convection Coefficient	–

Tire-specific data:

α_W	Pressure Sensitivity Exponent	–
β_W	Load Sensitivity Exponent	–
$b_{W,lin}$	Linear Speed Coefficient	–
$c_{W,quad}$	Quadratic Speed Coefficient	–
$c_{W,ambient}$	Temperature Sensitivity Coefficient	1/k
$\gamma_{W,conv}$	Convection Coefficient Exponent	–
m_W	Tire Mass	kg
$c_{W,heat,equiv}$	Specific Heat Capacity Of Tire	J/kg K
$k_{W,emp}$	Empirical Rolling Resistance Coefficient	1/K
$c_{W,aero}$	Air Resistance	N

Initial conditions:

$T_{W,init}$	Initial Temperature	C

2.27.3 Input and Output Variables

2.27.3.1 Mechanical Connection

$\dot{\boldsymbol{\varphi}}_{\mathbf{W,in}}$	Angular velocity of the wheel	rad/s
$\ddot{\varphi}_{\mathrm{W,in}}$	Angular acceleration of the wheel	rad/s^2
$\dot{\boldsymbol{\varphi}}_{\mathbf{W,out}}$	Angular velocity of a virtual wheel	rad/s
$\ddot{\varphi}_{\mathrm{W,out}}$	Angular acceleration of a virtual wheel	rad/s^2
$M_{\mathrm{W,in}}$	Torque on the drive side	Nm
$M_{\mathrm{W,out}}$	Vehicle forced moment	Nm

2.27.3.2 Data Input

$T_{\mathrm{W,ambient}}$	Ambient Temperature	K

2.27.3.3 Data Output

s_{W}	Slip Signal	%
$\dot{\boldsymbol{\varphi}}_{\boldsymbol{W}}$	Speed	rad/s
$M_{\mathrm{W,trans}}$	Wheel Torque	Nm
$T_{\mathrm{W,act}}$	Tire Temperature	K
$F_{\mathrm{W,act}}$	Wheel Load	Nm
P_{W}	Power	W
$P_{\mathrm{W,loss}}$	Power Loss	W
$F_{\mathrm{W,roll}}$	Rolling Resistance Force	N

2.27.4 Computation Variables

$S_{\mathrm{W,peak,act}}$	Actual slip of peak friction point for current road condition	–
$\mu_{\mathrm{W,asym,act}}$	Actual Asymptote of slip correction factor for current road condition	–
$C_{\mathrm{W,coeff1}}$	Wheel slip coefficient 1	–
$C_{\mathrm{W,coeff2}}$	Wheel slip coefficient 2	–
$v_{\mathrm{W,ref}}$	Reference Velocity	m/s
$F_{\mathrm{W,a}}$	Longitudinal force of tires	N
$F_{\mathrm{W,roll}}$	Rolling drag	N
$r_{\mathrm{W,dyn}}$	Corrected dynamic rolling radius	m

(continued)

$M_{W,trans}$	Torque transmitted by the wheel	Nm
$M_{w,roll}$	Rolling drag moment	Nm
$M_{w,slip}$	Slip moment	Nm
$M_{w,virt}$	Vehicle moment on a virtual wheel	Nm
$F_{W,roll}$	Instantaneous Rolling Resistance	N
$T_{W,act}$	Instantaneous Tire Temperature	K
$T_{W,stab}$	Stabilized Tire Temperature	K

2.27.5 Equation System

2.27.5.1 Dynamic Wheel Radius

There are two possibilities for determining the dynamic wheel radius.

1. Dynamic wheel base radius (Z_W=1)
   The dynamic wheel radius is constant for the whole speed range [2]:

$$r_{W,dyn} = r_{W,dyn,base} \tag{2.27.4}$$

2. Dynamic wheel radius map (Z_W = 2)
   The dynamic wheel radius *rW, dy*$_n$ is evaluated from the map for the actual wheel speed $\dot{\varphi}_{W,out}$2].

$$r_{W,dyn} = r_{W,dyn,list}(v_V) \tag{2.27.5}$$

2.27.5.2 Forces and Moments

Rolling Drag Moment [2]

$$M_{W,roll} = F_{W,in} \cdot c_{W,r}(v_{V,act}) \cdot r_{W,dyn} \tag{2.27.6}$$

The rolling resistance coefficient is evaluated out of the map $C_{w,f}(V_v)$ for the actual vehicle velocity.

The rolling resistance is defined as followed [2]:

$$c = c_v + c_\rho c_{RL} + c_T + c_p \tag{2.27.7}$$

c rolling resistance factor
c_V velocity proportional part

$c_v = c_v(v)$

$c\rho$ Rolling resistance influenced by side slip angle [2]:

$$c_\rho = \frac{m_{\text{vehicle}} \cdot v_{\text{vehicle}}^2}{\rho \cdot g} \cdot \text{abs}\left(\sin\left(\alpha_{f(r)}\right)\right) \tag{2.27.8}$$

$a_{f(r)}$ side slip angle

c_{RL} wheel load proportional part [2]:

$$c_{RL} = c_{RL}^* * \left(F_N - F_{N,Norm}\right)/F_N \tag{2.27.9}$$

c_{RL}^* reference wheel load proportional part

$F_{N,Norm}$ reference wheel load

c_T temperature proportional part [2]:

$$c_T = c_T(T_U) \tag{2.27.10}$$

c_p tire pressure proportional part [2]:

$$c_p = c_p^* * (p_{Norm} - p_{act})/p_{Norm} \tag{2.27.11}$$

c_{RL}^* factor at reference tire pressure

p_{Norm} reference tire pressure

p_{act} actual tire pressure (load-dependent definition in vehicle component)

Slip Moment

Wheel Slip function

For the current road condition ($\mu_{u,road}$) the Slip Characteristics can be evaluated from the $S_{W,peak}\left(\mu_{u,road}\right)$ and $\mu_{w,asym}\left(\mu_{u,road}\right)$

With this, we calculate the slip coefficients [2]:

$$C_{w,coeff1} = 2 - \frac{2 \cdot \arcsin\left(\mu_{w,asxm,act}\right)}{\pi} \tag{2.27.12}$$

$$C_{w,coeff2} = \frac{1}{S_{W,peak,act}} \cdot \tan\frac{\pi^2}{4 \cdot \left(\pi - \arcsin\left(\mu_{w,asym,act}\right)\right)} \tag{2.27.13}$$

Reference Velocity [2]

$$\text{If } \boldsymbol{v}_{\mathbf{V,act}} > \dot{\boldsymbol{\varphi}}_{\mathbf{W,in}} \cdot \boldsymbol{r}_{\mathbf{w,dyn}} \rightarrow \boldsymbol{v}_{\mathbf{W,ref}} = \boldsymbol{v}_{\mathbf{V,act}} \tag{2.27.14}$$

$$\text{Else} \rightarrow \boldsymbol{v}_{\mathbf{W,ref}} = \dot{\boldsymbol{\varphi}}_{\mathbf{W,in}} \cdot \boldsymbol{r}_{\mathbf{W,dyn}} \tag{2.27.15}$$

Current wheel slip

Independently from the operating mode the wheel slip results from [2]

$$s_W = \frac{\dot{\varphi}_{W,in} \cdot r_{W,dyn} - v_{V,act}}{v_{W,ref}} \quad \text{for} \quad |v_{W,ref}| < 10^{-4} s_W = 0 \tag{2.27.16}$$

Slip difference

The slip difference is defined as difference between the actual slip and the infinite slip with the peak friction value [2].

$$\Delta S_W = S_W - S_{W,peak,act} \tag{2.27.17}$$

Selection for different Δs_W [2]

$$\begin{aligned} \Delta S_W &< 0 \\ M_{w,slip} &= 0 \end{aligned} \tag{2.27.18}$$

$$\begin{aligned} \Delta S_W &\leq 0.03 \\ M_{W,slip} &= -SIGN(S_W) \cdot 5 \cdot 10^5 \times \Delta S_W^2 \end{aligned} \tag{2.27.19}$$

$$\begin{aligned} \Delta S_W &> 0.03 \\ M_{W,slip} &= -SIGN(S_W) \cdot 5 \times 10^5 \cdot 0.03 \cdot (2 \cdot \Delta S_w - 0.03) \end{aligned} \tag{2.27.20}$$

The Transmittable Longitudinal Wheel Force

This is the force value which can be transmitted by the wheel—road friction.

The maximum slip correction factor is [2]:

$$\begin{aligned} C_{W,lim} = \sin C_{W,coeff1} \cdot arctan\left(C_{W,coeff2} \cdot S_W\right) \\ \cdot \tanh\left[3.6 \cdot \left(v_{V,act}^2 + 0.0278 + \left(\dot{\varphi} \cdot r_{W,dyn}\right)^2 \cdot 0.02\right)\right] \cdot \end{aligned} \tag{2.27.21}$$

$$F_{w,pot} = F_{w,in} \cdot \mu_{w,tire} \cdot \mu_{u,road} \tag{2.27.22}$$

For the actual wheel slip, the maximum transmittable force is [2]:

$$F_{V,a,lim} = C_{W,lim} \cdot F_{W,pot} \tag{2.27.23}$$

The moment of the vehicle (acting at the virtual wheel with r =1 m) in defined as followed [2]:

$$M_{V,virt} = F_{V,a,lim} \cdot 1\,\text{m} \tag{2.27.24}$$

For the actual longitudinal force $F_{W,a}$

For the actual longitudinal force, the necessary slip correction factor can be calculated back [2]:

$$C_{W,act} = \frac{F_{W,a}}{F_{W,pot}} \tag{2.27.25}$$

$$C_{slip} = \frac{F_{W,a}}{F_{W,pot} \cdot C_{w,coeff1} \cdot C_{w,coeff2}} \tag{2.27.26}$$

if ($F_{w,a} > F_{V,a,lim}$) more longitudinal force should be transmitted as it is possible with the actual wheel slip.

For rolling resistance and slip together [2]:

$$M_{W,trans} = -\left(F_{W,a} \cdot r_{W,dyn} - M_{W,roll} - M_{W,lip}\right) \tag{2.27.27}$$

Wheel power

The wheel power is calculated out of the transmitted wheel torque and the wheel speed [2]:

$$P_{W,trans} = M_{W,trans} \cdot \dot{\varphi}_W \tag{2.27.28}$$

2.27.5.3 Rolling Resistance Model

Determination of the exterior diameter and the surface area [2]:

$$D_{W,design} = D_{W,seat} + \frac{2R_W \cdot W_W}{100} \tag{2.27.29}$$

$$A_W = D_{W,design} \cdot \pi \cdot W_W + 2\pi\left(\frac{D_{W,design}^2}{4} - \frac{D_{W,seat}^2}{4}\right) \tag{2.27.30}$$

The fundamental assumption of this detailed tire model is that the transient tire temperature response can be modeled in the same way as the steady state response to the ambient temperature [2]:

$$F_{W,roll} = F_{W,roll,stab}\left[1 + k_{W,emp}\left(T_{W,act} - T_{W,stab}\right)\right] \tag{2.27.31}$$

In order to calculate the instantaneous rolling resistance at each time step, the subsequent algorithm has to be followed:

(1) The **steady state rolling resistance value** $F_{W,roll,stab}$ at current conditions as a function of tire load $F_{W,act}$, tire inflation pressure $z_{V,load}$, tire translation speed $v_{W,act}$ and ambient temperature T_U [2]:

$$\begin{aligned} \boldsymbol{F_{W,roll,stab}} = \boldsymbol{c_{W,roll,ISO}} \cdot \boldsymbol{F_{W,act}} \left(\frac{\boldsymbol{p_{act}}}{\boldsymbol{p_{W,ISO}}}\right)^{\alpha_W} \left(\frac{\boldsymbol{F_{W,act}}}{\boldsymbol{F_{W,ISO}}}\right)^{\beta_W} \\ \cdot \left[1 + \boldsymbol{b}\left(\frac{\boldsymbol{v_{W,act}} - \boldsymbol{v_{W,ISO}}}{\boldsymbol{v_{W,ISO}}}\right) + \boldsymbol{c}\left(\frac{\boldsymbol{v_{W,act}} - \boldsymbol{v_{W,ISO}}}{\boldsymbol{v_{W,ISO}}}\right)^2\right] \\ \cdot \left[1 + \boldsymbol{c_{W,ambient}}\left(\boldsymbol{T_{W,ISO}} - \boldsymbol{T_U}\right)\right] \end{aligned} \tag{2.27.32}$$

in which the coefficients $c_{W,roll,ISO}$, $p_{W,ISO}$, $v_{W,ISO}$, $T_{W,ISO}$, $b_{W,lin}$, $c_{W,quad}$, α_W, β_W and $c_{W,ambient}$ are unique to each tire. The subscript ISO simply refers to the parameters value under ISO (or actual) test conditions. Naturally these values must be furnished along with the model coefficients.
In the above equation, we have not yet added the aerodynamic drag. Since the aerodynamic drag is assumed independent of temperature, it is added after the instantaneous rolling resistance is calculated.

(2) The stabilized tire temperature $T_{W,stab}$ is equal to [2]:

$$T_{W,stab} = T_U + \frac{v_{W,act} \cdot F_{W,roll,stab}}{C_{W,conv} \cdot A_W} \tag{2.27.33}$$

where [2]:

$$c_{W,conv} = c_{W,conv,ISO}\left(\frac{v_{W,act}}{v_{W,ISO}}\right)^{\gamma} \tag{2.27.34}$$

and $c_{W,conv,ISO}$, γ and A_W are unique to each tire. For the case of $v_{W,act} = 0$ it is necessary
To apply a free convection exchange coefficient. In this case, we first calculate the Rayleigh number [2]:

$$Ra_D = \frac{g \cdot \beta_W \left(T_{W,act} - T_U\right) \cdot D^3_{W,design}}{v\alpha} \tag{2.27.35}$$

with [2]:

g gravitational constant (9.81 m/s^2)

β_W volumetric thermal expansion coefficient of air (which can be approximated as $\frac{2}{T_{W,act}+T_U}[K^{-1}]$

v [m/s^2] kinematic viscosity of air (evaluated at $\frac{T_{W,act}+T_U}{2}$ through interpolation in a table)

α [m/s^2] thermal diffusivity of air (evaluated at $\frac{T_{W,act}+T_U}{2}$ through interpolation in a table)

Then the Nusselt number and subsequently the heat transfer coefficient are calculated [2]:

$$Nu_D = 0.15 Ra_D^{0.333} \tag{2.27.36}$$

$$c_{W,heat} = \frac{Nu_D \cdot k_{W,therm}}{D_{W,design}} \tag{2.27.37}$$

with

$k_{W,therm}$ [W/mK] thermal conductivity of air (evaluated at $\frac{T_{W,act}+T_U}{2}$ through interpolation in a table)

(3) The **instantaneous average tire temperature at each time increment** is then obtained by integrating [2]:

$$T_{W,act}(t) - T_{W,act,last} = \frac{1}{m_W \cdot C_{W,heat,equiv}} \int_0^t \left[F_{W,roll} \cdot v_{W,act} - c_{W,heat} \cdot A_W \left(T_{W,act,last} - T_U \right) \right] d\tilde{t} \tag{2.27.38}$$

with

$c_{W,heat,equiv}$ equivalent specific heat of the tire [J/kg K]

(4) Once the instantaneous tire temperature is calculated, the instantaneous rolling resistance is calculated by [2]:

$$F_{W,roll} = F_{W,roll,stab} \left[1 + k_{W,emp} \left(T_{W,act} - T_{W,stab} \right) \right] \tag{2.27.39}$$

(5) Concluding the (temperature-independent) aerodynamic drag is added to receive the final, entire **instantaneous rolling resistance** [2]:

$$F_{W,roll} = F_{W,roll} + c_{W,aero} \left(\frac{v_{W,act}}{v_{W,ISO}} \right)^2 \tag{2.27.40}$$

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2. AVL Cruise (2009) Theory manual, AVL list GmbH, Graz, Austria, Document no. 04.0108.2009, Edition 06.2009

3. Patton KJ, Nitschke RG, Heywood JB, Development and evalu-ation of a friction model for spark-ignition engines. SAE Paper No. 89-0836
4. Shayler PJ, Christian SJ, Ma T, A model for the investigation of temperature heat flow and friction characteristics during engine warm-up. SAE Paper 93-1153
5. Shayler PJ, Leong DKW, Murphy M (2003) Friction teardown data from motored engine tests on light duty automotive diesel engines at low temperatures and speeds. In: ASME 2003, Fall Technical Conference

Chapter 3
Virtual Powertrain Design

The drivetrain configuration is freely definable and the user can build in as many clutches, torque converters, or elastic shafts as required.

The drivetrain configuration is like a standard vehicle with a manual gearbox. In this configuration, only one clutch is allowed. In front and after the clutch, there can only be one degree of freedom. In addition, just one gearbox is allowed in this configuration. The standard manual gearbox was developed for shifting in the next gear according to the engine speeds. In addition, check that the friction clutch is directly connected to the gearbox.

The drivetrain configuration is like a standard vehicle with an automatic gearbox. In this configuration, only one torque converter is allowed. In front and after the torque, converter there can only be one degree of freedom. In addition, just one gearbox or one Continuously Variable Transmission (CVT) is allowed in this configuration. For the different configurations, different calculation algorithms are used. Thus the calculation times can be decreased for standard drivetrains [1].

Standard automatic was developed for shifting according to speeds in the next gear. In addition, the torque converter is directly connected to the gearbox or the CVT.

In the User Area (Fig. 3.1) click on the Projects folder with the right mouse button and select new project. Enter a name and select OK. The new name will appear in the projects tree. Select this new project with the right mouse button and select new version. Enter the new version name or keep the default version name. Select OK. Select the version with the right mouse button and select save. All files and subdirectories required for the project management are created [2].

In the navigation frame there is current default project directory with tree structure, showing all existing subfolders, projects, and versions in that directory. On the right side of the window, there are detailed data regarding objects in the tree structure.

To start a new project, in User tab with right mouse click popup menu, select new and chose project or version and create project or version with new name. For already existing project, load project or version by selecting the desired version of the project from project tree structure in User view [1].

After starting AVL CRUISE platform, select Desk tab and click to Vehicle Model to open Desk Area to begin building the new model.

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_3

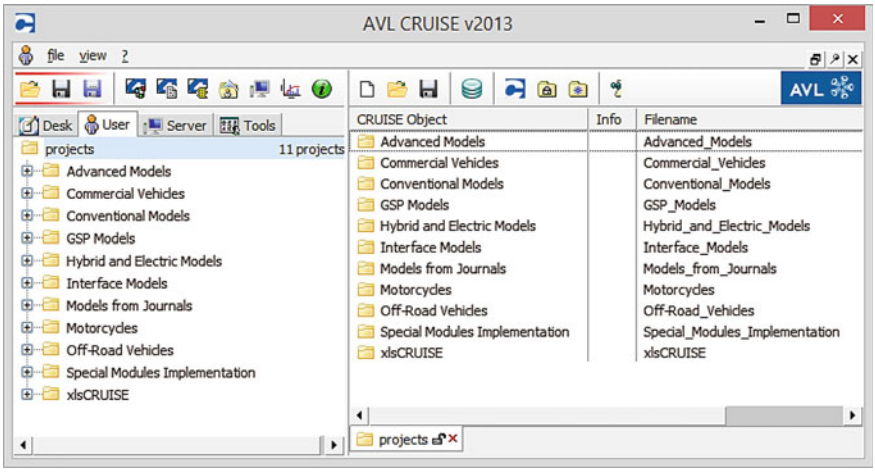


Fig. 3.1 User Area

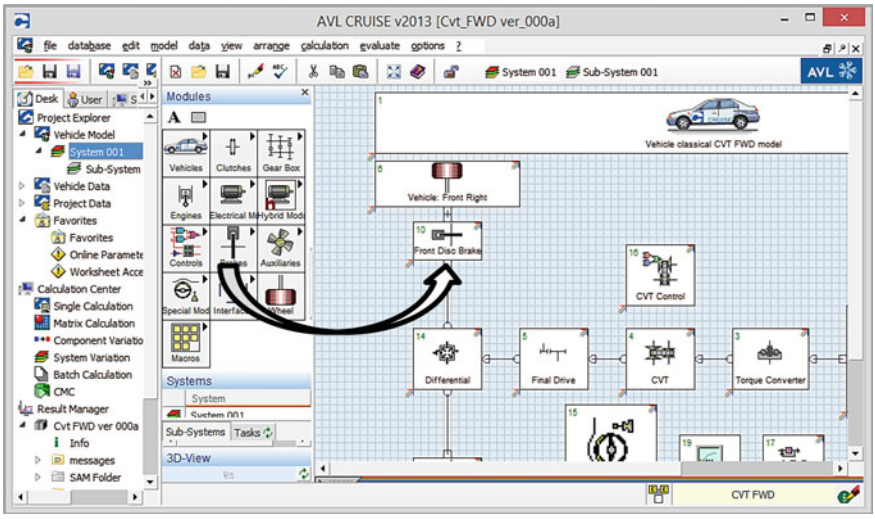


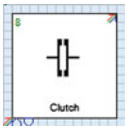
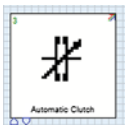
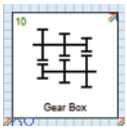
Fig. 3.2 Desk Area

To insert component into model click on the Desk Area (Fig. 3.2) and then click on the Vehicle Model.

The components used to build the models are located under the Desk Area—Modules Sidebar, and are described in Table 3.1.

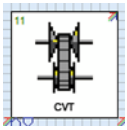
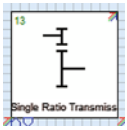
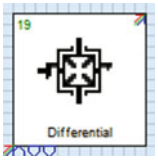
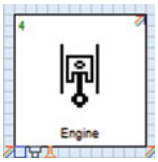
In addition to the components of the drivetrain, whose single modules are defined by a Configuration File at the program start, there are general modules on each view which corresponds to a vehicle.

Table 3.1 Components Description

Symbol	Component
Category Vehicles	
	**Vehicle**: The vehicle is the basic component of every model. In this component, the general data of a model like the nominal dimensions or the weights are defined. Only one vehicle component is required in a model. Road resistances and dynamic wheel loads are calculated for road and dynamometer runs based on the dimensions and the load state. The wheel loads are calculated considering motion. The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated.
Category Clutches	
	**Clutch**: The clutch contains a model for a friction clutch as it is used in vehicle with manual gearboxes. In this case, the clutch is controlled by the driver via the cockpit. The clutch can also be used together with a CVT gearbox and it is only necessary for starting. In this case, the clutch is controlled by the control module CVT control. The clutch slips to compensate for the difference in the rotational speeds of engine and drivetrain when the vehicle is set in motion.
	**Torque Converter**: employ the force represented by a moving fluid to transmit engine torque. As these devices compensate for differences in the rotating speeds of engine and drivetrain, they are ideal for effecting the transition from stationary to mobile operation. The torque converter also multiplies torque. First, pump converts the mechanical energy emanating from the power unit into fluid energy; a second transformation, back into mechanical energy.
	**Automatic Clutch**: The automatic clutch is used as the starting clutch in vehicles. This component holds a model of an uncontrolled automatic clutch which is often used as the starting clutch (centrifugal clutch) in vehicles. The transferable torque is based on the speed ratio between input and output considering the mass moments of inertia. The clutch torque is described by characteristics which depend on the speed ratio between input and output.
	**Shaft**: is used to make elastic connections between different components and for the study of low-frequency dynamic effects in the drivetrain, which are caused by shifting gears. Shaft connections in the drivetrain can be modeled to be rigid or elastic at torsion. The clearance in elastic shaft connections can also be taken into account. The torsional stiffness of the shaft depends on the length of the shaft.
Category Gearbox	
	**Gearbox**: Gear transmissions featuring several fixed ratios can maintain a correspondence between the respective performance curves for engine and vehicle. The component gearbox contains a model for a gearbox with different gear steps. The gearbox can be used for a manual or automatic gearbox. When used as an automatic gearbox, the gear shifting process will be controlled by the control module gearbox control or gearbox program.

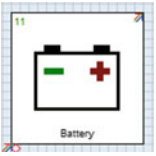
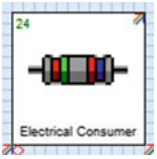
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Table 3.1 (continued)

Symbol	Component
	**CVT**: The Continuously Variable Transmission can convert every point on the engine's operating curve to an operating curve of its own, and every engine operating curve into an operating range within the field of potential driving conditions. With the model of the CVT gearbox it is possible to change the transmission between two user-defined threshold values. The adjusting speed between different transmissions is internal fixed at a constant value.
	**Single Ratio (Transmission Step)**: The Single Ratio Transmission is a gear step with fixed ratio. It can be used as a transmission step of the differential (final drive unit). A drive torque will be transferred to a power take-off torque of the transmission step by considering the transmission, the mass moments of inertia and the loss moments. The transmission ratio can be changed by multiplication with an additional factor and is defined by the number of teeth of input and output.
	**Differential (Power Divider)**: The division of one drive torque into two power take-off torques will be done by considering the transmission, the moments of inertia. The differential unit compensates for discrepancies in the respective rotation rates of the drive wheels: between inside and outside wheels during cornering and between different drive axles on 4WD vehicles. This wheel then responds to the application of excessive force by spinning.
	**Planetary Gear**: The planetary gearbox belongs to the power split devices. It consists of three main components: the sun gear, the planet carrier and the ring gear. This gearbox can be used in hybrid systems, where vehicles are be driven using different power supplies. With the planetary gear, it is possible to add torque and speed with different directions at the transmission input shafts. The speed ratio and the direction of rotation can be changed according to which member is fixed.
Category Engines	
	**Engine**: The internal combustion engine will be modeled by means of characteristic curves and maps. This component contains a model for a internal combustion engine. The characteristic curves for the full load, the fuel consumption, and others can be freely defined by the user. It is possible to define a gasoline engine as well as a diesel engine. In this component, a temperature model is included to consider the influence of the temperature on the fuel consumption and emissions while the engine is cold.
	**Boost Engine**: The Boost engine component supplies a connection to the engine cycle simulation AVL BOOST and enables a coupling with the BOOST combustion engine model in AVL CRUISE. Additionally, the AVL CRUISE user can start the pre- and postprocessors of AVL BOOST by pressing the appropriate button, thereby using all the features of AVL BOOST. Engine maps can be either precalculated or then used as stationary maps or the calculation can run online considering all the transient effects.

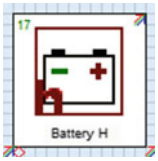
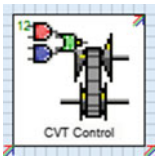
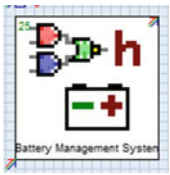
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Table 3.1 (continued)

Symbol	Component
Category Electrical Modules	
	**Electric Motor**: Can be used for electrically driven vehicles, cars with hybrid drive or to operate auxiliaries such as a fan or an oil pump. The electric motor is defined by means of characteristic curves. Therefore, different motor type models can be constructed. Efficiency map is dependent on the speed and the voltage. Map of the output torque dependent on the speed and the voltage. Efficiency map is dependent on the speed and the voltage.
	**Generator**: The generator must furnish the vehicle's electrical system with a sufficient supply of current under all operating conditions. The objective is to achieve balanced charging the curves for performance and speed-frequency response must be selected to ensure that the amount of current generated under actual operating conditions. The current delivered by the generator results from a map dependent on the speed and the main voltage.
	**Battery**: The battery must be capable of limited-duration high-current delivery for starting, and it must be able to furnish some or all of the electrical energy for other important system components for limited periods with the engine at idle or off. The lead-acid storage battery represents the usual means of meeting these demands. The instantaneous charge of the battery is determined by means of a balance computation. The charge capacity is the nominal capacity of the battery.
	**Electrical Consumer**: Electric consumers are represented as ohmic resistors in the onboard network. They represent an electric current loss. The number of resistors that can be defined is user dependent. The resistors can be fixed by a constant value or by means of characteristic curves. It is possible to define resistors as a function of any external input value. It is also possible to define an external switch that switches the resistor on and off depending on exceeding an external value.
Category Hybrid Modules	
	**Electric Machine**: The electric machine component can be used either as an electric motor or as a generator. There are separate characteristic maps for each mode. Together with the battery H and supercapacitor components, the user can simulate hybrid systems. The model of the electric machine contains two components, the inverter and the electric motor. For this type of model, a characteristic map for the efficiency is used to calculate the loss of power.
	**Supercapacitor**: This component is a capacitor with a very high capacity. It stores energy in electrostatic fields and can reach a very high power density (up to 1 kW per kg). The thermal behavior of the supercapacitor is described by a thermal substitution model. Single cells can be modeled as well as any combination of them. The supercapacitors cell structure is kind of a matrix with a constant number of rows and a constant number of cells in each row.

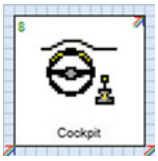
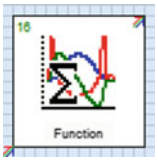
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Table 3.1 (continued)

Symbol	Component
	**Battery H**: The basic model consists of a voltage source and an ohmic resistance. Internal resistance can be defined either as a constant value or as a temperature dependent function. The resistance is constructed in a way that a big part of the complex processes within the battery are taken into consideration. The thermal behavior of the battery is described by a thermal substitution model. Single cells can be modeled as well as any combination of them.
Category Controls	
	**Gearbox control**: The gearbox control is required to define an automatic gearbox. In the gearbox control, the gear shifting process can be defined automatically without any influence of the driver. The gearbox control shifts the gears dependent on a speed or velocity. In the calculation tasks it is decided which of the two shifting strategies is used. The speed, respectively, which velocity is used can be defined via the Data Bus connection.
	**Gearbox program:** This is used for automatic gearboxes in combination with the gearbox control. The gearbox program allows for a more complicated gear shifting process than the gearbox control, as the load signal of the engine is considered. The gearbox program shifts the gears according to given curves as a function of the load signal and the engine speed. The target gear determined by the program is transmitted to the gearbox control that transmits it to the gearbox.
	**CVT control**: This component controls the CVT gearbox. The transmission of the CVT can be defined as function of the vehicle velocity and the throttle position. The CVT is controlled by definition of desired input speed depending on velocity and load signal. When using this option, the Data Bus input channel input speed has to be connected. Multiple transmission ratio maps can be handled in a single simulation by changing the value of input signal.
	**ASC (Anti-Slip Control)**: This component controls the coefficient of friction of the single wheels. For the maximum value, the throttle position or the clutch release is changed. The ASC checks the force transmission factor (ratio between force that should be transmitted and maximum transmittable force) of all connected wheels (driven wheels). If the force that has to be transmitted exceeds the adhesion limit, the load signal or the clutches release change.
	**PID control**: Combined with other signal processing components (function component), the PID control may be used to build-up more powerful control subsystems in AVL CRUISE. It basically supports two operation modes. The first mode is the standard PID control mode, using the difference between a desired value and an actual value to generate an output value. The second mode is the advanced signal control with limitation mode.
	**Battery Management System**: This component serves to control energy flow from/to the battery. The desired current limits from/to the battery can be defined as function of any set parameter so that the electric loads (like electric machine) can adapt themselves to. For the set parameter, the type of data and the units can be selected by a special input dialog. The lower and upper thresholds of State of Charge determine the operation area of the battery.

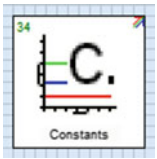
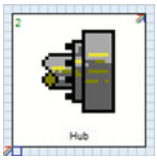
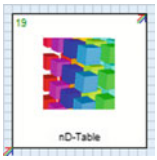
(continued)

Table 3.1 (continued)

Symbol	Component
Category Brakes	
	**Brake**: The brake component is described by brake data and dimensions. It is possible to define drum brakes as well as disk brakes. The braking torque is computed considering the braking dimensions and the input brake pressure. This brake pressure can come from the cockpit component or brake control. The brake calculation always stays dynamic and never switches to a kinematic connection. The brake is controlled by the brake pressure which has to be supplied via Data Bus input.
Category Special Modules	
	**Cockpit**: The cockpit links the driver and the vehicle. In this component, connections are only made via the Data Bus connection. On one hand, the driver gets information such as the vehicle velocity and the vehicle acceleration. On the other hand, information from the driver such as the pedal positions is delivered to other components. The pedal positions (clutch pedal position) are transferred into corresponding indicators (clutch release) via the pedal characteristics (clutch pedal).
	**Exhaust System**: Exhaust systems consider the effects of the catalytic converter and soot filler on the raw emissions of the engine. Starting with the temperature of the catalytic converter, factors for the conversion will be computed for the single emissions components on the basis of the temperature dependent maps. The heat loss coefficient is the percentage of the exhaust energy delivered by the engine which reaches the exhaust system.
	**Map**: The component map interpolates a user-defined function which can be one or two dimensional. It has two Data Bus inputs for the independent function variables and one output for the interpolated function value. In the case of a one-dimensional function the second Data Bus input is ignored. The type of data can be selected by a special input dialog. Please note that all data coming via the Data Bus are in SI units. The conversion to the defined unit in the map is then done in the component.
	**Steplike Map**: The map is defined as a group of curves. The first column contains the curve parameters, which can be interpreted as the curve height (z-value). The points belonging to the same curve share the same parameter value. The second and the third columns contain the x and y values. This group of curves separates the domain into sections with constant z-values, equal to parameter of the lower boundary curve (lower means smaller z-value).
	**Function**: The component function can be used for calculating with user-defined functions. There are two possibilities to define the function: in RPN-notation style (Reverse Polish Notation) where only one function output y can be defined and programming in C-style, where up to 99 function outputs can be defined. Those arguments must be connected to form the function term by using operators which can be selected from a selection menu.

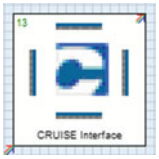
(continued)

Table 3.1 (continued)

Symbol	Component
	**Constants**: Up to 99 constants can be defined which can be used by other components via Data Bus. Every constant requires the definition of the Data Bus channel number, a comment, the constant value, the unit and the data type. Data type can be of integer, double or string. In the case of a string constant, the unit definition is not used in calculation. The constant output values are sent to the Data Bus and can be used by other components.
	**Monitor**: The monitor can be introduced, if the calculation run must be detected. It is possible to show some results of the calculation while the calculation is running. This is done via the online monitor. It is possible to connect up to ten input channels of the monitor to output channels of different components that are available at the AVL CRUISE Data Bus. The output in the online monitor is only available in the form of tables. More than one monitor component can be used in a AVL CRUISE model.
	**Hub**: The component hub is a combination of a brake and a virtual wheel. It is used in models with an interface to a co-simulating program which simulates the environment, the vehicle and the wheel. The component has the Data Bus inputs braking torque and (wheel) resistance torque which can be connected with an interface component like AVL CRUISE interface or CM-Car. When set to dynamic, the brake calculation always stays dynamic and never switches to a kinematic connection.
	**nD-Table**: The component n-dimensional lookup table interpolates a user-defined function which can be up to ten dimensions. It has ten Data Bus inputs for the independent function variables and five Data Bus outputs for the interpolated function value. In the case of less than ten input connected, the leftover Data Bus are ignored. The component n-d lookup table serves for the input of general maps. These maps can have from one to ten independent input values.
Category Interfaces	
	**AVL Exhaust System**: The component AVL Exhaust System extends the AVL CRUISE library in order to meet all user requirements regarding emissions (more detailed and accurate results). The component supplies a connection to the after treatment system of AVL BOOST and enables a coupling with the BOOST after treatment model in AVL CRUISE. By naming a BOOSTDLL and a model file (*.atm), the BOOST after treatment system can be started from AVL CRUISE in the form of a coupled calculation.
	**MATLAB®/Simulink™**: The interface that allows integrating controllers and/or mechanical elements, such as special drives, into the computational model of AVL CRUISE. The input and output variables will be transferred by means of inports and outports. As two simulations, for AVL CRUISE and MATLAB®, take place at the same time in this case, the integration steps of the two programs will have to be harmonized by a suitable selection of the step width.

(continued)

Table 3.1 (continued)

Symbol	Component
	**AVL CRUISE Interface**: The AVL CRUISE interface component defines the interface between AVL CRUISE models calculated in client mode with AVL CRUISE DLL and the calling applications. In every time step, AVL CRUISE data goes to the server application through up to 99 Data Bus input channels AVL CRUISE to environment, and from there, data comes back to AVL CRUISE through up to 99 output channels environment to AVL CRUISE which can be connected with AVL CRUISE components.
	**CarMaker Interface**: The CM-Car component defines the interface in co-simulation between AVL CRUISE powertrain models calculated with the SAM calculation task and the CarMaker simulation package. In every time step, AVL CRUISE data goes to the CarMaker application through Data Bus input channels AVL CRUISE to CarMaker, and from there, data comes back through output channels CarMaker to AVL CRUISE which can be connected to the other components.
	**TruckMaker Interface**: The CM-Truck component defines the interface in co-simulation between AVL CRUISE powertrain models calculated with the SAM calculation task and the TruckMaker simulation package. In every time step, AVL CRUISE data goes to the TruckMaker application through Data Bus input channels AVL CRUISE to TruckMaker, and from there, data comes back through output channels TruckMaker to AVL CRUISE which can be connected to the other components.
	**CarSim Interface**: The CarSim component defines the interface in co-simulation between AVL CRUISE powertrain models calculated with the SAM Calculation Task and the CarSim simulation package. In every time step, AVL CRUISE data goes to the CarSim application through Data Bus input channels AVL CRUISE to CarSim, and from there, data comes back to AVL CRUISE through output channels CarSim to AVL CRUISE which can be connected to the other AVL CRUISE components.
	**TruckSim Interface**: The TruckSim component defines the interface in co-simulation between AVL CRUISE powertrain models calculated with the SAM calculation task and the TruckSim simulation package. In every time step, AVL CRUISE data goes to the TruckSim application through Data Bus input channels AVL CRUISE to CarSim, and from there, data comes back to AVL CRUISE through output channels CarSim to AVL CRUISE which can be connected to the other AVL CRUISE components.
	**AVL PUMA Interface**: The AVL PUMA component serves as an interface to AVL PUMA Open engine testbed automation system and it is based on the existing AVL CRUISE interface component. AVL PUMA Open is the application-oriented automation system for the engine, powertrain and vehicle testbeds of AVL. In addition to standard features such as fully automated test runs or manual operation, the AVL PUMA Open automation system provides reliable and precise control of measuring devices and test cell facilities.

(continued)

Table 3.1 (continued)

Symbol	Component
	**ETAS Interface**: component defines the interface between AVL CRUISE models calculated in client mode and the calling applications. In every time step, AVL CRUISE data goes to the server application through up to 99 Data Bus input channels AVL CRUISE to ETAS, and from there, data comes back to AVL CRUISE through up to 99 output channels which can be connected with AVL CRUISE components. This interface offers a variety of possibilities to the user, for example, modeling of a testbed configuration in ETAS Labcar.
	**NI VeriStand Interface**: component defines the interface between AVL CRUISE models calculated in client mode with AVL CRUISE DLL and the calling applications. In every time step, AVL CRUISE data goes to the server application through up to 99 Data Bus input channels, and from there, data comes back to AVL CRUISE through up to 99 output channels which can be connected with AVL CRUISE components.
	**AVL DRIVE**: The component AVL DRIVE enables an evaluation of the drivability of AVL CRUISE results. This evaluation is possible only in simulation mode, and therefore only in the tasks which provide this mode. Before evaluation start, a model must be parametrized also in AVL DRIVE. AVL DRIVE is only launched when activation is selected. This functionality is used for calibration of the model in AVL CRUISE without doing a AVL DRIVE evaluation every time.
	**Black Box**: Similar to the interface for MATLAB®/Simulink™, the Black Box component allows to process program codes provided by the user, third parties (C or Fortran) or a dynamic link (DLL or SO). These Black Boxes are called several times per time step and can be used for purely logical functions which do not depend on the last call. These Black Boxes are called only once per time step and can be used if any memory effects should be considered.
Category Wheel	
	**Wheel**: The wheels and tires link the vehicle to the road. The wheel component considers many influencing variables and their effect on the rolling state. The moment of rolling drag can be computed on the basis of the wheel load, the corrected dynamic rolling radius, and the coefficient of rolling drag. The longitudinal tire force results from the friction coefficient, the wheel load as well as from the wheel load factor and the slip factor.

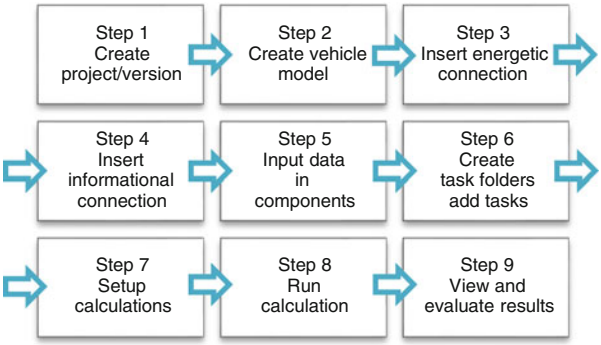


Fig. 3.3 Work process flow

In the Vehicle Modeler, the components are organized in component groups and they can simply be dragged and dropped onto the working area, where they can be linked together to represent the desired drivetrain configuration.

To build a new model in AVL CRUISE, the recommended work process flow to create a project/version is described in Fig. 3.3.

To connect the components, the user must click with the right mouse button on connector of the first component to be connected and chose connect (or break the established connections, or cloning the pin if are more of them needed). Drag the connection with the mouse toward to desired component. Click with the left mouse button on connector of the second component to be connected.

There are two types of connections: energetic connections (mechanical connection—blue, exhaust connection—gray, electrical connection—red), and informational connection (red–green–blue).

Energetic connections which transfer energy are divided by the type of energy which is transferred into the following groups (mechanical, exhaust, electrical) and are established by polylines between the pins.

Information to the Data Bus is the only informational connection. These connections are established by an arrow which shows the information flow. The energetic connections are represented in form of lines on the screen [3].

The components with informational connections have only a small colored arrow on the left bottom corner of the symbol. For connecting the different modules with information flow, open the Data Bus dialog by double clicking with the left mouse button on the colored lines (red—green—blue) at the bottom of the vehicle modeler (Fig. 3.4).

The connections in the data bus are described as follows: in the first column (component … requires) all components are listed which need information from other components (e.g., IC Engine). In the second column (input information … from), all values required by this component will be displayed (e.g., Throttle Position). Values that are marked in blue in this column have to be connected; values marked in black are optional. After selecting a value in the second column,

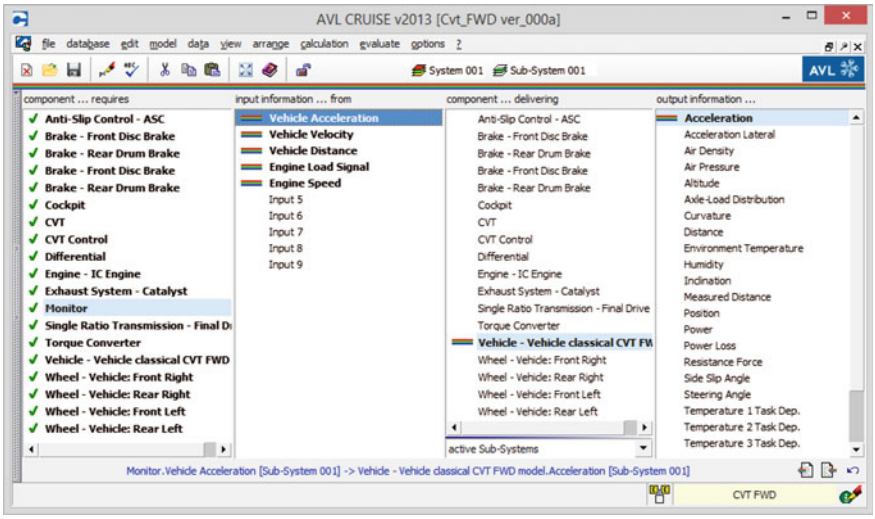


Fig. 3.4 Data Bus window

in the third column (component … delivering) all components appear which can deliver such information (e.g., Cockpit; in this case the only component that can deliver a throttle position). In the fourth column (output information …), the values appear that can deliver this information (e.g., Throttle Position).

In AVL CRUISE a preselection is done so that only the components that can provide the input information as requested in the second column are presented in the third and fourth columns (in this case, only the Cockpit can deliver an information like the throttle position). For this, the Cockpit delivers the information about the actual throttle position to the engine, where it is used to determine the output torque.

Click on a components Data Bus symbol (input or output) with the left mouse visualizes the Data Bus connections between this component and other components (Fig. 3.5). The channels appear as colored lines and also their names are written. Freezing visualization is possible by clicking on the connection icon until other connection is selected.

Components can be encoded using the button in the upper left corner of the components window. The user can define a password with a maximum length of eight characters. Encrypted components cannot be opened until the correct password is entered. If a model which contains encrypted components is calculated, all results can be viewed except the results of the encrypted components. Macrocomponents can also be encrypted using the right mouse button [1].

Components and their connections can be grouped into subsystems. The subsystems can be activated or deactivated so that several configurations of an active subsystem can be defined. With these three subsystems it is possible to define two

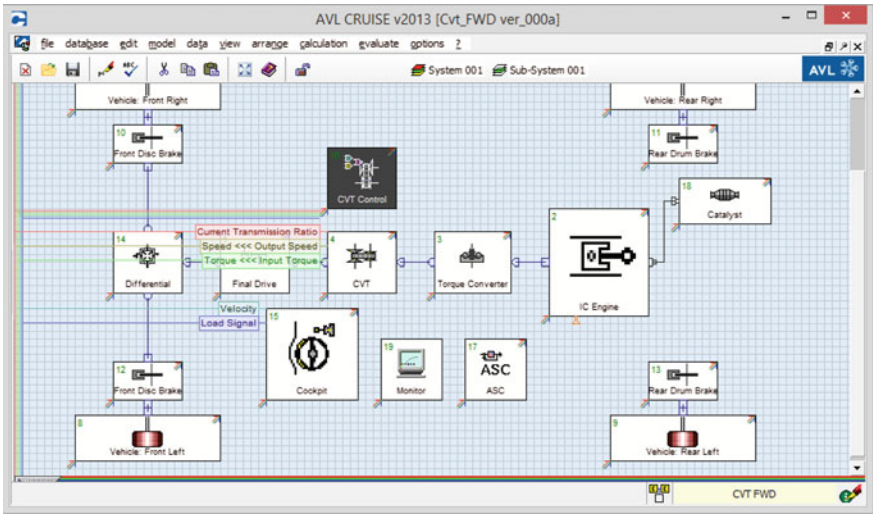


Fig. 3.5 Data Bus visualization

vehicle configurations, which are from now on called systems. The structure of the systems/subsystems and their activation status is shown i

- Conventional System, containing the subsystems:
  - Main (activated);
  - Manual Transmission (activated);
  - Hybrid (deactivated).
- A Hybrid System, containing the active subsystems:
  - Main (activated);
  - Manual Transmission (deactivated);
  - Hybrid (activated).

n the navigation tree and also in the "Systems" section of the sidebar of the vehicle modeler.

Each component of the model has a popup menu accessible by right mouse button click (Fig. 3.6).

Special components which have the sheet description of Data Bus (Function, Map, Interface Components, etc.) have user-defined channel names.

The Kinematic Chain Browser can be launched in the popup menu of a selected component (Fig. 3.7). All mechanical connections starting from the selected component are shown in a tree structure in the left side of the window. When a second component is selected in the tree structure, all speeds between the selected components are shown in the table in the right side of the window, each row representing one gear of the gearbox [1].

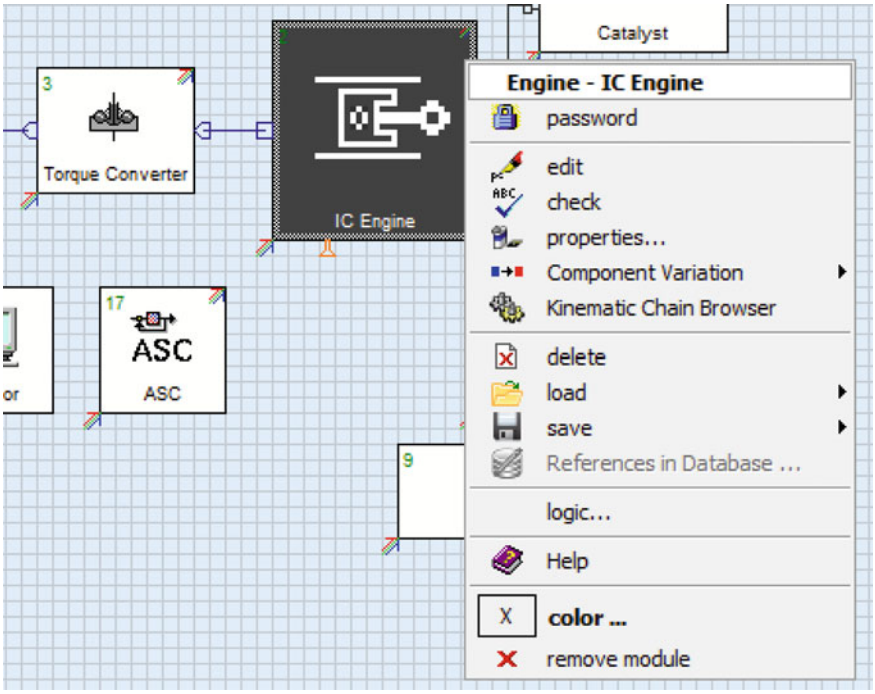


Fig. 3.6 Component popup menu

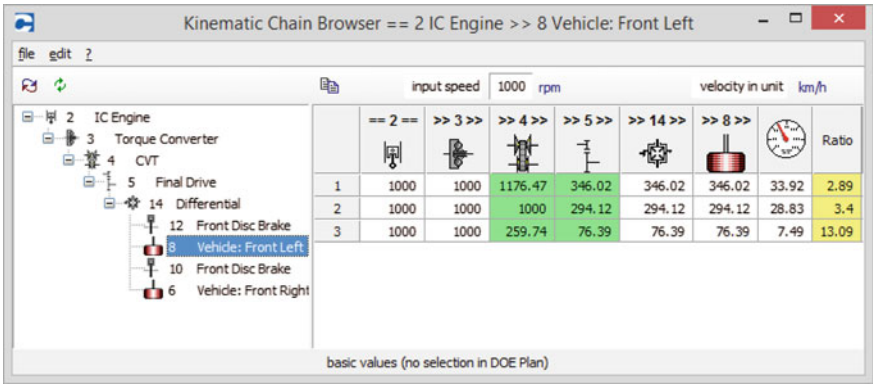


Fig. 3.7 Kinematic Chain Browser

Speed values of components which have an influence on the speed (Gearbox, Single Ratio Transmission) are marked green. The last column of the table shows the entire speed ratio. The input speed can be defined manually, default value is 1000 rpm.

Direction is shown with arrows above component icons. The direction can be changed by sorting it in the tree structure. This can be done by double clicking on a module in the tree or by clicking on the button. The selected module will then become the new root module. In the head of the table, symbols indicate in which direction the modules are calculated: >> X >> forward, << X << backward.

If the component data has been changed, the Kinematic Chain Browser can calculate once more and update its results when pressing the update button.

The Kinematic Chain Browser also takes into account the ratio changes of the Component Variation or Matrix Calculation. When opening the Kinematic Chain Browser, the ratios of the basic model are taken for the calculation. When a certain variation case is selected in the variations DoE plan, the chain browser calculates with the ratios of that case.

Activation and deactivation of Task Folders and tasks within Task Folders is always related to the actual system. Definition can be done in the sidebar of the vehicle modeler: after the selection of a system, its Task Folders and tasks can be activated/deactivated in the 'Tasks' sheet of the sidebar (Fig. 3.8).

Cycle Run (Fig. 3.9) is a calculation task for the fuel consumption and emissions calculation. This is done for a fixed driving profile. The determination of this profile has to be entered as function of the time. This task should be used especially for

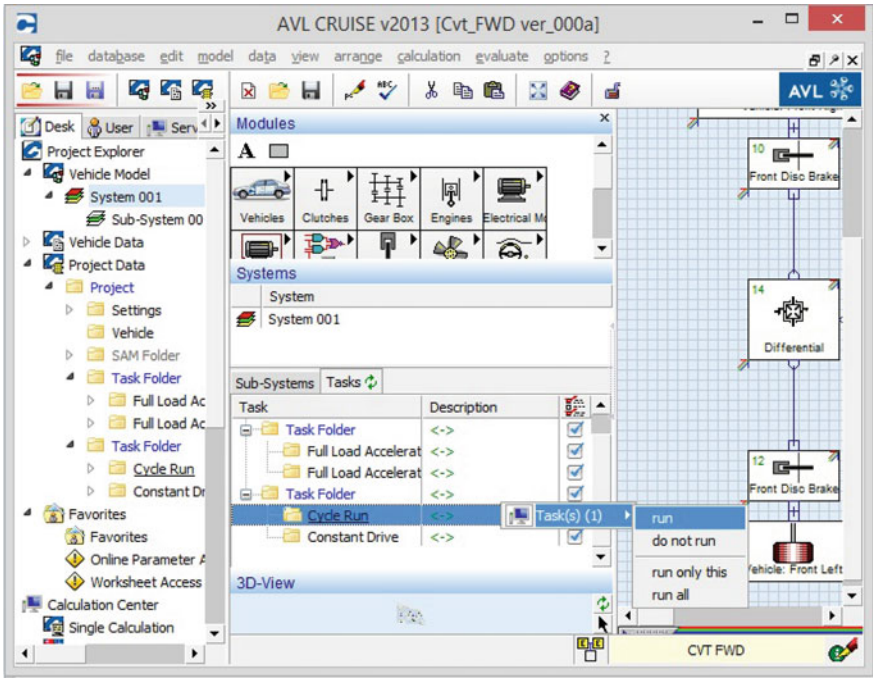


Fig. 3.8 Task Folders

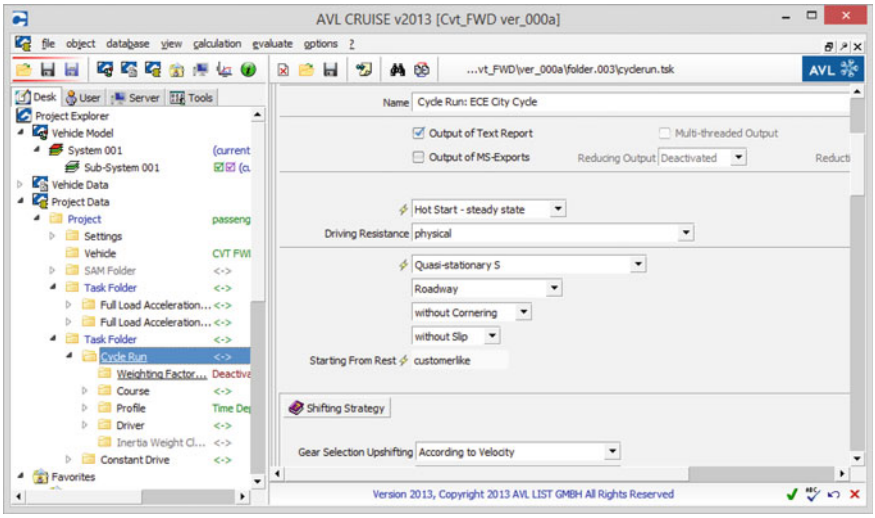


Fig. 3.9 Cycle Run

evaluations of standard driving profiles. The Cycle Run can be calculated as quasi-stationary and simulation. It is possible to select chassis dynamometer or road. Just as for the Driving Profile, a Gear Selection Mode can be stated.

The Cycle Run additionally depends on: Course, Profile and Driver. In this task, the behavior of the vehicle when following a velocity profile is observed. The reference axis is time [1].

Course component characterizes the environment and the driving conditions as function of the driving distance or time (Fig. 3.10). Among other things, the instantaneous atmospheric pressure and density as well as the temperature are acquired to describe the ambient conditions [1].

These variables are based upon the values existing at standard conditions, which will be adopted or computed according to the input.

All inputs are functions of the driving distance or time. If cornering is chosen, the angle of approach must be declared.

The Profile data (Fig. 3.11) should be entered as function of the time or distance. The following data is required [1]:

- Velocity: the rated of vehicle velocity;
- Gear: actual gear for shifting according to profile for manual gearboxes or gearbox control;
- Shifting Time: for manual gearboxes this shifting time is used if it is above the ergonomic border of the driver;
- Start Signal: to switch the engine on and off during the cycle;
- Minimum and maximum velocity: to set the threshold values that may not be exceeded during the test run;

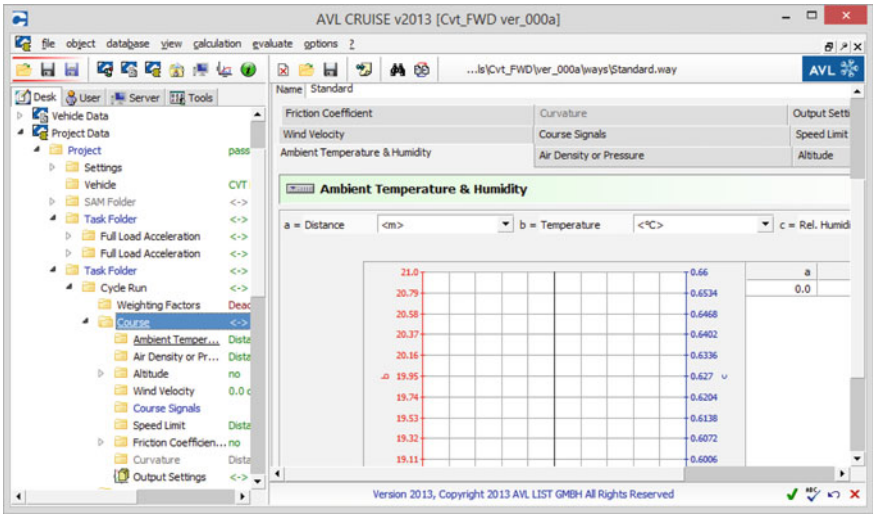


Fig. 3.10 Course component

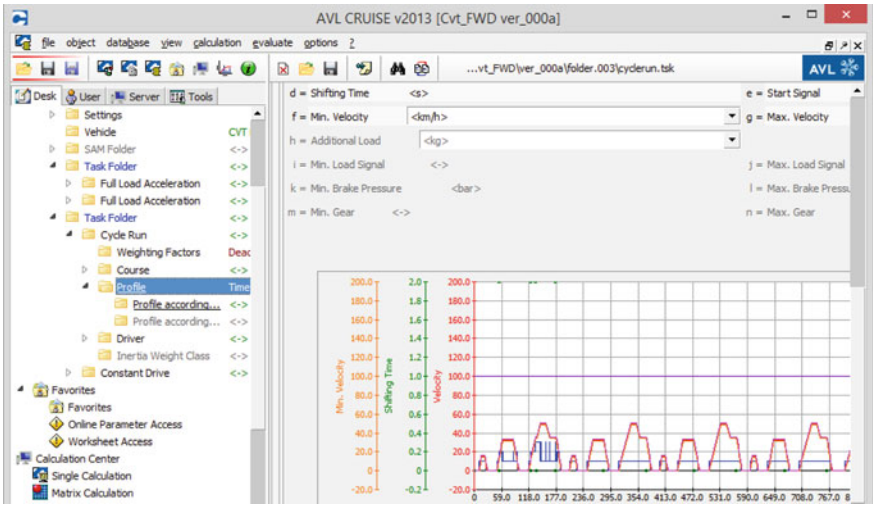


Fig. 3.11 Profile data

- Stop Time: (only for distance-dependent profile) for a distance-dependent profile stop times of the vehicle can be defined;
- Additional Load: is defined as a function of time or distance and added to the load of the empty vehicle. This type of load definition can be activated in the tasks “Cycle Run” and “Cruising”.

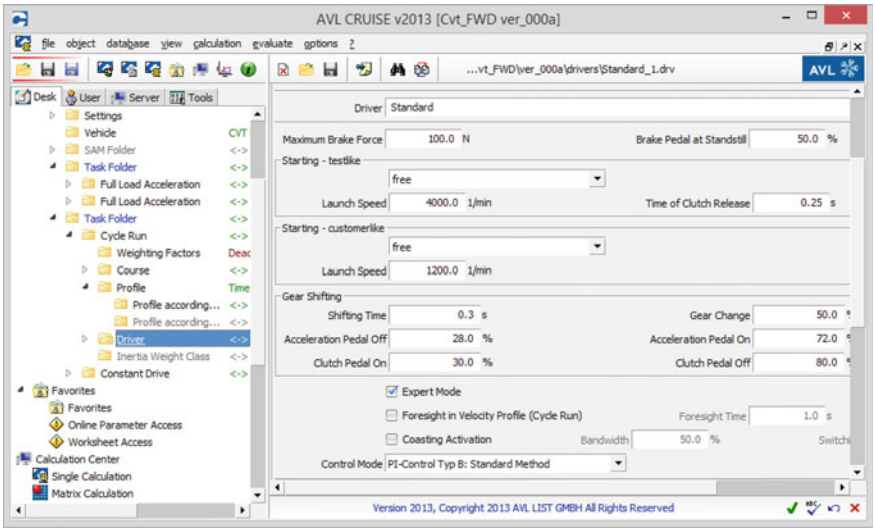


Fig. 3.12 Driver

The Driver should imitate the behavior of a real driver as well as possible (Fig. 3.12). For this purpose, the behavior can be defined by different input data. The used data can be divided into the following groups:

- Data defining the shifting behavior;
- Data defining the starting behavior;
- Data defining the driving behavior.

The data for the starting and driving behavior can be defined by the user (expert mode) or default values can be used (standard) [1].

Simulation allows modeling of the real behavior if the overall model is harmonized correspondingly. This will automatically lead to a control loop in which the driver (modeled as Driver Module in the program) acts as a controller when simulating a real driving task. For this the driver has to change the acceleration, brake, or clutch pedal position.

In the elastic connections, the torsional stiffness of the connection (shafts) can be taken into account.

To solve the differential equation system, a single-step integration method has been implemented. This method calculates the actual conditions and the conditions of the next time step. If the accuracy limits cannot be reached with the chosen time step width (check with a second integration method), the time step width is decreased [1].

If the temporary results cause a change of the lock conditions, the equation system is switched to a new one.

General Configurations are models without any restrictions in the build-up of the model. The calculation is done without special knowledge about the drivetrain.

In general, all component specific calculations are done in the respective modules. The values which are determined in the modules are combined together to an equation system with the smallest possible number of degrees of freedom. The integration for this reduced system can be done independent of the external modules in the internal equation solver.

References

1. AVL Cruise (2011) Users Guide, AVL List GmbH, Graz, Austria, Document no. 04.0104.2011, Edition 06.2011
2. AVL Cruise (2011) Release Note, AVL List GmbH, Graz, Austria, Document no. 04.0102.2011, Edition 06.2011
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Chapter 4
Classical Powertrain Configuration Model and Simulation

4.1 Classical Vehicle Model

4.1.1 Classic CVT Model

This chapter describes how to create and run the model of a manual front wheel drive. To place a component in the working area, click on the component group with the left mouse button, move the mouse over the required component, and then click and drag the component into the vehicle model area. Arrange the components as shown in Fig. 4.1 and connect the components as specified in the diagram.

Place the following components in the working area: Vehicle (1), IC Engine (2), Torque Converter (3), CVT Continuously Variable Transmission (4), Final Drive (5), Vehicle Front Right (6), Vehicle Rear Right (7), Vehicle Front Left (8), Vehicle Rear Left (9), Front Disk Brake (10), Rear Drum Brake (11), Front Disk Brake (12), Rear Drum Brake (13), Differential (14), Cockpit (15), CVT Control (16), ASC Anti-Slip Control (17), Catalyst (18), and Monitor (19).

There are three types of energy connections: mechanical, exhaust, and electrical and are made by connecting polylines between the pins.

All the connections in the Data Bus for this model are described in Table 4.1 [1]. Validation of the connections are marked using bold and are required for the functioning of the model.

Vehicle (1) is one of the main objects in a model. This component contains general data of the vehicle, such as nominal dimensions and weights. Only one vehicle component is required in a model. Road resistances and dynamic wheel loads are calculated for road and dynamometer runs based on the dimensions and the load state. The wheel loads are calculated considering motion. The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated [2].

To define component input data (Table 4.2) double click on the icon or click on it the right mouse button and select edit to open the following window (Fig. 4.2).

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_4

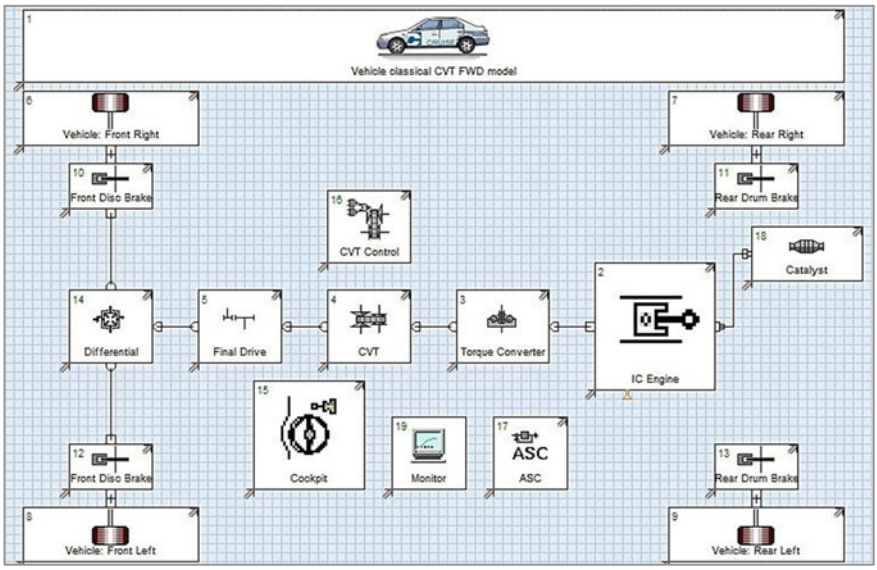


Fig. 4.1 Complete CVT model

The properties window is accessed through properties button in the input data window, or from the pop-up menu by selecting "Properties". Selected parameters have an influence on the needed component data input for calculation (Fig. 4.3). With these settings it is also possible to run a calculation with minimal input data, as the input fields of the unavailable data can be switched off.

IC Engine (2) component contains a model for an internal combustion engine. The characteristic curves for the full load, fuel consumption, and others can be freely defined by the user. It is possible to define a gasoline engine as well as a diesel engine. In this component a temperature model is included to consider the influence of the temperature on the fuel consumption and emissions while the engine is cold. The engine will be modeled by a structure of characteristic curves and maps [2]. To define component input data (Table 4.3) double click on the icon or click on it with the right mouse button and select edit to open the following window (Fig. 4.4).

To load IC Engine characteristic click on the Full Load Characteristic tab (Fig. 4.5). Select (kW) unit from the b column using pull-down menu. Add rows by clicking on and enter the following data (Table 4.4).

The Motoring Curve (Fig. 4.6) will be defined similar to the Full Load Characteristic as power versus engine speed (Table 4.5). Engine Maps Basic data can be loaded from the folder projects\CVT_FWD\CVT_FWD.dbf [1].

In the Fuel Consumption Map (Fig. 4.7, Table 4.6) the actual fuel consumption for stationary operation is listed depending on the brake mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—volume flow (l/h)).

Table 4.1 Data Bus connection

Component requires	Input information	Component delivering	Output information
ASC	**Load signal**	Cockpit	Load Signal
	Slip Signal Front Left	Wheel Front Left	Slip Signal
	Slip Signal Front Right	Wheel Front Right	Slip Signal
Brake Front Disk	**Brake Pressure**	Cockpit	Brake Pressure
Brake Rear Drum	**Brake Pressure**	Cockpit	Brake Pressure
Brake Front Disk	**Brake Pressure**	Cockpit	Brake Pressure
Brake Rear Drum	**Brake Pressure**	Cockpit	Brake Pressure
Cockpit	**Gear Indicator**	CVT	Current Gear
	Operation Control 0	IC Engine	Operation Control
	Speed	IC Engine	Engine Speed
CVT	**Desired Transmission**	CVT Control	Desired Transmission
CVT Control	**Current Transmission**	CVT	Current Transmission
	Load Signal	Cockpit	Load Signal
	Speed	CVT	Output Speed
	Torque	CVT	Input Torque
	Velocity	Cockpit	Velocity
IC Engine	**Load Signal**	ASC	Load Signal
	Start Switch	Cockpit	Start Switch
Monitor	Vehicle Acceleration	Vehicle	Acceleration
	Vehicle Velocity	Vehicle	Velocity
	Vehicle Distance	Vehicle	Distance
	Engine Load Signal	IC Engine	Actual Load Signal
	Engine Speed	IC Engine	Engine Speed
Torque Converter	Desired Clutch Release	CVT Control	Desired Clutch Release

Table 4.2 Vehicle component input data

Name	Value	Unit
Gas Tank Volume	0.05	m^3
Distance from Hitch to Front Axle	2970.0	mm
Height of Support Point at Bench Test	100.0	mm
Wheel Base	2250.0	mm
Distance of Gravity Center empty/half/full	900.0/910.0/920.0	mm
Height of Gravity Center empty/half/full	550.0/545.0/540.0	mm
Height of Hitch empty/half/full	420.0/410.0/400.0	mm
Tire Inflation Pressure Front Axle	2.2	bar
Tire Inflation Pressure Rear Axle	2.2	bar
Curb Weight	970.0	kg
Gross Weight	1410.0	kg
Frontal Area	1.80	m^2
Drag Coefficient	0.35	–

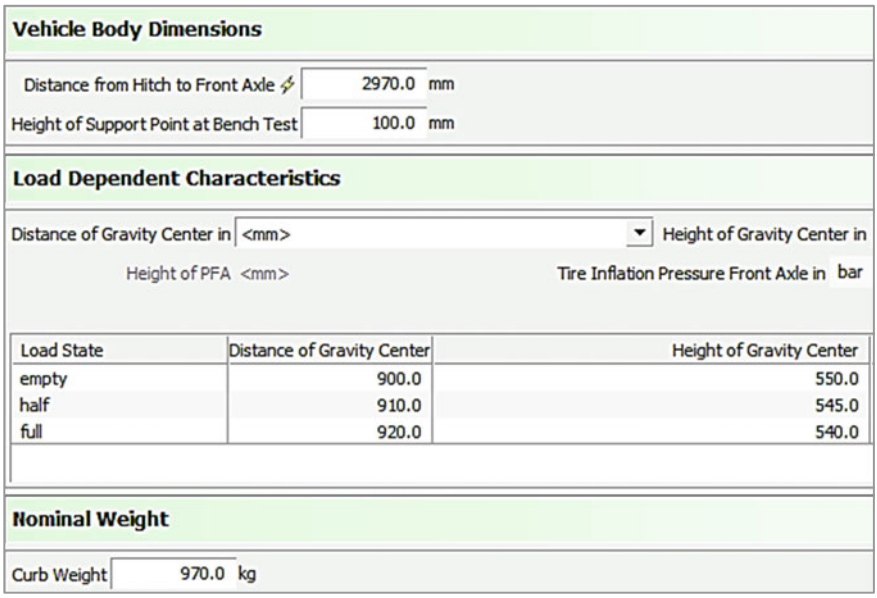


Fig. 4.2 Vehicle input data specifications window

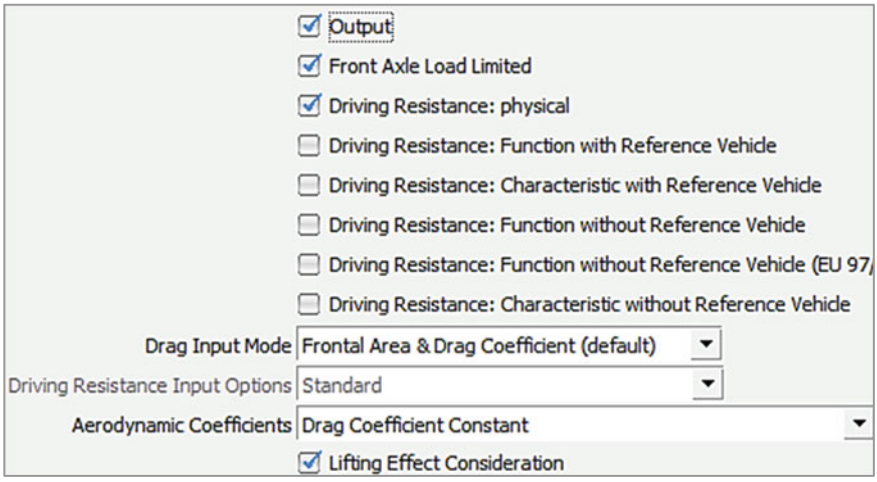


Fig. 4.3 Properties of Vehicle

This representation is used to make a unique relation between the Brake Mean Effective Pressure (BMEP) and the fuel consumption for a given engine speed. The Fuel Consumption Map can also be defined as a Specific Consumption Map (Fig. 4.8, Table 4.7).

Table 4.3 IC Engine components input data

Name	Value	Unit
Engine Displacement	1360.0	cm^3
Engine Working Temperature	80.0	°C
Number of Cylinders	4	–
Number of Strokes	4	–
Idle Speed	800.0	1/min
Maximum Speed	6000.0	1/min
Inertia Moment	0.1	kg m^2
Response Time	0.1	s
Heating Value for Gasoline	44500.0	kJ/kg
Fuel Density	0.737	kg/l
Idle Consumption	1.0	l/h
Idle Emission NO_x	0.02	kg/h
Idle Emission CO	0.10	kg/h
Idle Emission HC	0.01	kg/h
Lower Speed for Fuel Shut-Off	1300.0	1/min
Upper Speed For Fuel Shut-Off	1400.0	1/min

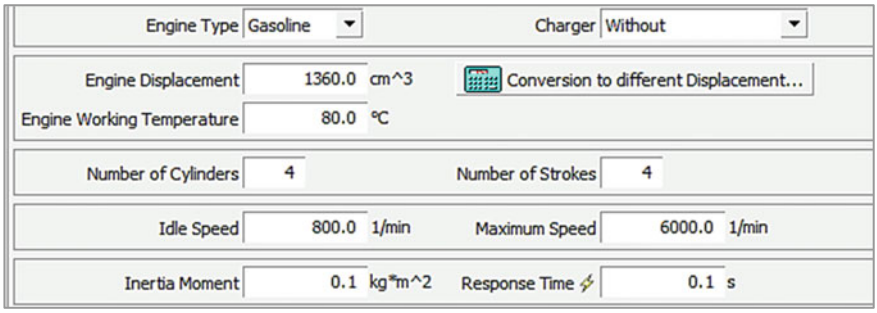


Fig. 4.4 IC Engine input data specifications window

The Specific Consumption Map can be loaded according to the following parameters a—speed (1/min), b—BMEP (bar), c—specific volume flow (l/kWh). The specific fuel consumption map is only used when the corresponding switch is activated [1].

In the emission maps the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—mass flow (kg/h), namely NO_x emission map in Fig. 4.9 and Table 4.8, CO emission map in Fig. 4.10 and Table 4.9, HC emission map in Fig. 4.11 and Table 4.10 [1].

The **Torque Converter** (3) employs the force represented by a moving fluid to transmit engine torque (Fig. 4.12). As these devices compensate for the differences between the engine speed and drivetrain, they are ideal for the transition from

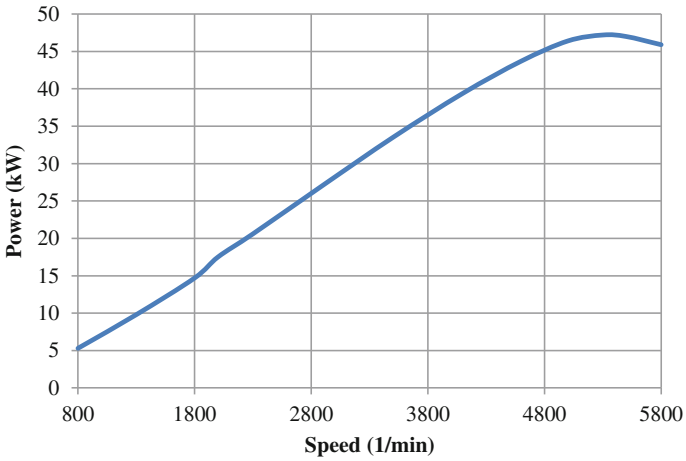


Fig. 4.5 Full Load Characteristic

Table 4.4 Full Load Characteristic data

Speed (1/min)	Power (kW)	Speed (1/min)	Power (kW)
800.0	5.3	4100.0	39.4
1300.0	9.8	4600.0	43.7
1800.0	14.7	5000.0	46.4
2000.0	17.5	5300.0	47.2
2300.0	20.6	5500.0	47.0
2900.0	27.1	5800.0	45.9
3500.0	33.5	6000.0	43.8

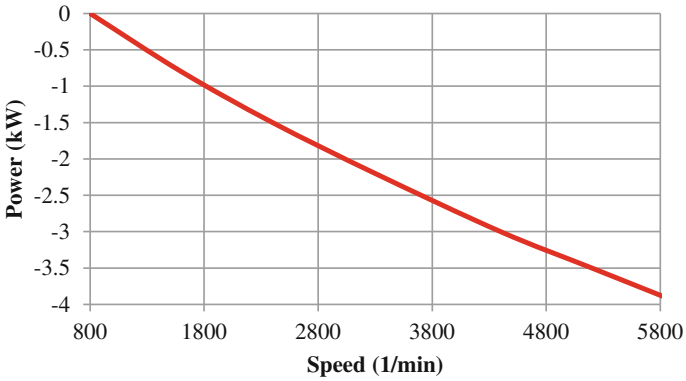


Fig. 4.6 Motoring Curve

Table 4.5 Motoring Curve data

Speed (1/min)	Power (kW)
800.0	0.0
1600.0	−0.8
2400.0	−1.5
3300.0	−2.2
4400.0	−3.0
5200.0	−3.5
6000.0	−4.0

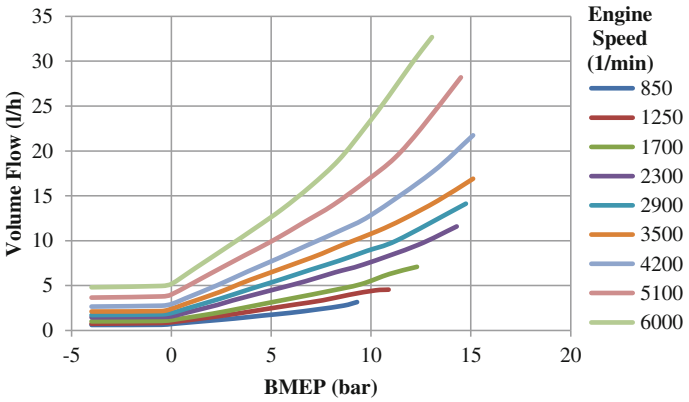


Fig. 4.7 Fuel Consumption Map

stationary to mobile operation. The torque converter also multiplies torque. First, an impeller (pump) converts the mechanical energy from the power unit into fluid energy (hydraulic fluid); a second transformation, back into mechanical energy, occurs using the turbine blades [2].

These devices offer economical exploitation when used together with mechanical variable ratio transmissions; operation with nonpositive engagement (slip) is limited for better efficiency. The torque on the converter input and output depends on the speed ratio between pump and turbine as well on the absolute angular velocity of the pump (a—speed ratio (-), b—torque ratio (-), c—pump torque (-) as shown in Fig. 4.13 and Table 4.11) [1].

To define component input data (Table 4.12) double click on the icon or click on it with the right mouse button and select edit to open the following window.

CVT (4) can convert every point on the engine operating curve to an operating curve of its own, and every engine operating curve into an operating range within the field of potential driving conditions (Fig. 4.14). Its advantage over conventional

Table 4.6 Fuel Consumption Map data

(a)											
850	(b)	−4.0	−0.5	0.0	1.6	3.2	4.6	6.0	7.3	8.6	9.3
	(c)	0.6	0.7	0.8	1.0	1.3	1.6	2.0	2.3	2.8	3.2
1250	(b)	−4.0	−0.5	0.0	1.8	3.3	4.7	7.6	8.9	10.2	10.9
	(c)	0.7	0.8	0.9	1.4	1.9	2.4	3.4	4.0	4.5	4.6
1700	(b)	−4.0	−0.5	0.0	2.1	3.5	4.9	7.8	9.5	10.9	12.3
	(c)	1.0	1.1	1.2	1.9	2.5	3.1	4.3	5.1	6.3	7.1
2300	(b)	−4.0	−0.5	0.0	2.3	3.1	5.3	8.2	9.6	12.3	14.3
	(c)	1.4	1.5	1.6	2.8	3.3	4.6	6.5	7.3	9.5	11.6
2900	(b)	−4.0	−0.5	0.0	2.4	4.0	5.5	8.4	9.8	11.3	14.8
	(c)	1.7	1.8	1.9	3.5	4.6	5.7	7.8	8.9	10.0	14.1
3500	(b)	−4.0	−0.5	0	2.4	4.0	7.1	10.3	11.6	13.4	15.1
	(c)	2.1	2.2	2.4	4.3	5.7	8.1	11.0	12.4	14.5	16.9
4200	(b)	−4.0	−0.5	0	2.4	4.0	7.1	10.3	11.6	13.4	15.1
	(c)	2.7	2.8	2.9	5.1	6.6	8.0	11.2	12.8	17.6	21.7
5100	(b)	−4.0	−0.5	0	3.6	5.1	6.6	9.8	11.2	12.5	14.5
	(c)	3.7	3.8	4.0	8.3	10.0	12.0	16.7	19.2	22.6	28.2
6000	(b)	−4.0	−0.5	0	2.8	4.2	5.5	8.4	9.7	12.1	13.1
	(c)	4.8	5.0	5.2	9.2	11.4	13.5	19.0	22.7	29.8	32.7

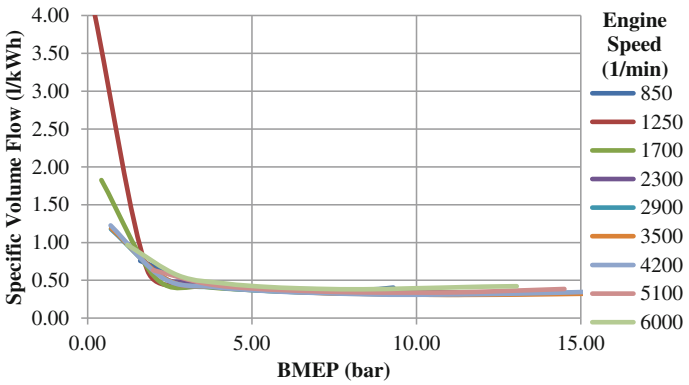


Fig. 4.8 Specific Consumption Map

fixed-ratio transmissions lies in the potential for enhancing performance and fuel economy while reducing exhaust emissions [2].

To define component input data (Table 4.13) double click on the icon or click on it with the right mouse button and select edit to open the following window [1].

Table 4.7 Specific Consumption Map data

(a)										
850	(b)	1.60	3.16	4.55	5.95	7.32	8.63	9.30	–	–
	(c)	0.76	0.50	0.43	0.39	0.38	0.38	0.40	–	–
1250	(b)	0.19	1.82	3.32	4.73	6.17	7.59	8.90	10.21	10.88
	(c)	4.07	0.63	0.46	0.41	0.38	0.36	0.36	0.35	0.34
1700	(b)	0.42	2.06	3.54	4.89	6.33	7.83	9.48	10.93	12.30
	(c)	1.83	0.54	0.42	0.37	0.35	0.33	0.32	0.34	0.34
2300	(b)	0.73	2.30	3.07	5.25	6.71	8.21	9.63	13.34	14.29
	(c)	1.18	0.54	0.48	0.34	0.36	0.35	0.34	0.34	0.36
2900	(b)	0.71	2.42	3.47	5.49	6.97	8.41	9.81	11.29	14.75
	(c)	1.18	0.51	0.41	0.36	0.34	0.32	0.32	0.31	0.33
3500	(b)	0.72	2.41	3.97	7.04	8.59	10.31	11.61	13.35	15.11
	(c)	1.19	0.51	0.41	0.33	0.32	0.31	0.31	0.31	0.32
4200	(b)	0.70	2.31	3.82	5.34	6.90	8.53	9.99	13.06	15.11
	(c)	1.23	0.53	0.41	0.36	0.33	0.32	0.31	0.32	0.35
5100	(b)	1.99	3.62	5.10	6.63	8.12	9.77	11.19	12.53	14.50
	(c)	0.63	0.45	0.39	0.36	0.34	0.34	0.34	0.36	0.39
6000	(b)	1.21	2.76	4.18	5.53	8.39	9.72	10.88	12.05	13.05
	(c)	0.97	0.56	0.46	0.41	0.38	0.39	0.40	0.41	0.42

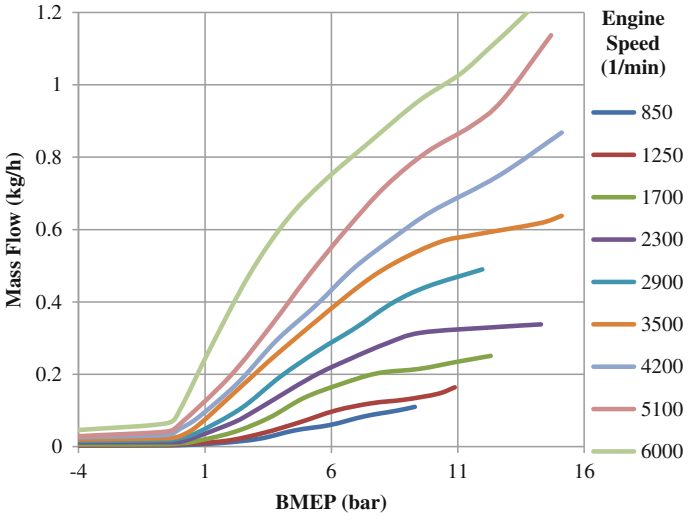


Fig. 4.9 NO_x emission map

Table 4.8 NO_x emission map data

(a)											
850	(b)	−4.0	−0.5	0.00	1.61	3.16	4.55	5.95	7.32	8.62	9.30
	(c)	0.00	0.00	0.00	0.01	0.02	0.05	0.06	0.08	0.10	0.11
1250	(b)	−4.0	−0.5	0.00	1.82	3.32	4.73	6.17	8.90	10.2	10.9
	(c)	0.00	0.01	0.01	0.02	0.04	0.07	0.10	0.13	0.15	0.16
1700	(b)	−4.0	−0.5	0.00	0.42	2.08	4.89	7.83	9.48	10.1	12.3
	(c)	0.01	0.01	0.01	0.01	0.04	0.13	0.20	0.22	0.23	0.25
2300	(b)	−4.0	−0.5	0.00	0.73	2.20	5.24	8.21	9.55	12.4	14.3
	(c)	0.01	0.01	0.01	0.03	0.07	0.19	0.29	0.32	0.33	0.34
2900	(b)	−4.0	−0.5	0.00	0.70	2.41	5.47	8.41	9.81	12.0	15.2
	(c)	0.02	0.02	0.02	0.04	0.11	0.27	0.40	0.44	0.49	0.58
3500	(b)	−4.0	−0.5	0.00	0.68	2.41	7.05	8.59	11.6	14.3	15.1
	(c)	0.02	0.02	0.03	0.06	0.17	0.44	0.51	0.59	0.62	0.64
4200	(b)	−4.0	−0.5	0.00	0.75	2.31	5.41	8.53	9.99	12.6	15.1
	(c)	0.03	0.03	0.05	0.08	0.18	0.39	0.58	0.65	0.75	0.87
5100	(b)	−4.0	−0.5	0.00	1.97	3.62	6.65	9.77	11.5	12.8	14.7
	(c)	0.03	0.04	0.06	0.19	0.34	0.61	0.81	0.89	0.96	1.14
6000	(b)	−4.0	−0.5	0.00	1.21	2.76	5.68	9.43	12.3	13.5	14.2
	(c)	0.05	0.07	0.10	0.27	0.48	0.73	0.95	1.11	1.18	1.23

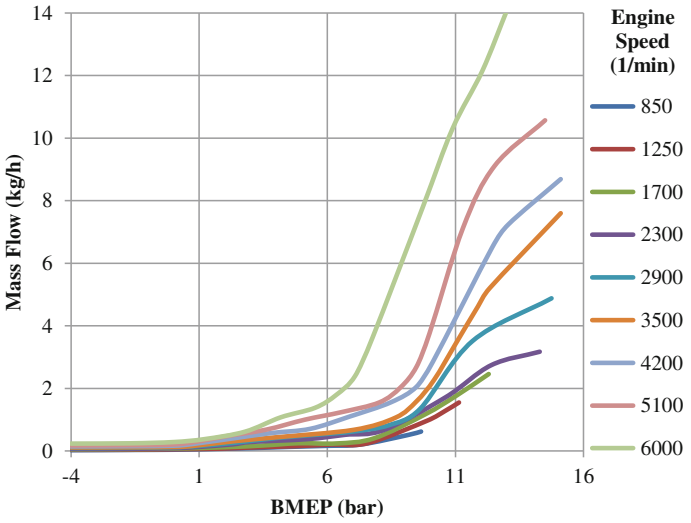


Fig. 4.10 CO emission map

Table 4.9 CO emission map data

(a)											
850	(b)	−4.0	−1.6	0.00	1.60	3.16	4.55	5.95	7.32	9.18	9.66
	(c)	0.03	0.03	0.04	0.07	0.10	0.13	0.17	0.21	0.52	0.62
1250	(b)	−4.0	−1.7	0.00	1.82	4.73	6.16	7.59	9.89	10.6	11.1
	(c)	0.04	0.04	0.06	0.08	0.15	0.21	0.25	0.97	1.28	1.55
1700	(b)	−4.0	−1.7	0.00	2.06	4.89	6.37	7.83	9.82	11.0	12.3
	(c)	0.05	0.06	0.08	0.12	0.25	0.24	0.41	1.17	1.76	2.46
2300	(b)	−4.0	−1.7	0.00	0.73	2.30	5.22	8.21	10.6	12.4	14.3
	(c)	0.06	0.07	0.09	0.12	0.21	0.38	0.67	1.72	2.74	3.17
2900	(b)	−4.0	−1.7	0.00	0.85	2.42	5.52	8.42	9.62	11.7	14.8
	(c)	0.10	0.10	0.12	0.15	0.27	0.52	0.83	1.35	3.52	4.88
3500	(b)	−4.0	−1.7	0.00	0.72	2.41	7.04	10.2	11.9	12.3	15.1
	(c)	0.11	0.12	0.13	0.16	0.32	0.68	2.28	4.62	5.21	7.60
4200	(b)	−4.0	−1.7	0.00	0.72	3.82	6.88	9.48	10.1	13.1	15.1
	(c)	0.15	0.15	0.17	0.22	0.57	1.10	2.05	2.85	7.24	8.69
5100	(b)	−4.0	−1.7	0.00	1.00	3.62	6.55	8.86	9.48	11.3	12.5
	(c)	0.18	0.19	0.21	0.31	0.68	1.24	2.03	2.69	7.14	9.11
6000	(b)	−4.0	−1.7	0.00	1.21	4.18	6.35	7.77	9.72	12.1	13.1
	(c)	0.24	0.25	0.29	0.38	1.08	1.79	3.63	7.78	12.2	14.2

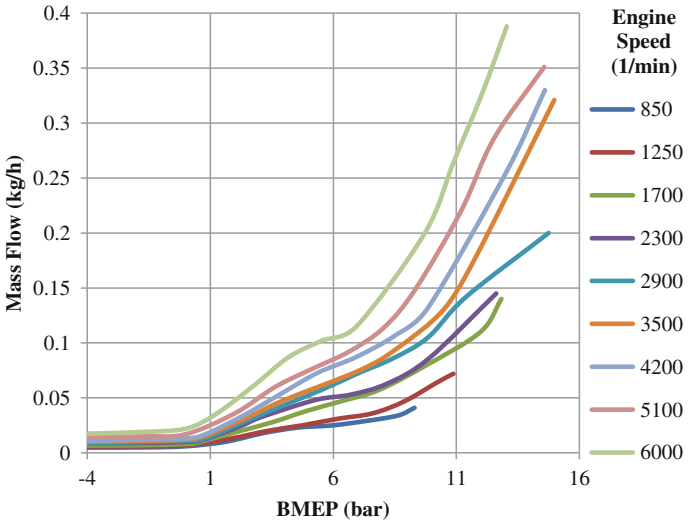


Fig. 4.11 HC emission map

Table 4.10 HC emission map data

(a)											
850	(b)	−4.0	−1.6	0.00	1.60	3.16	4.55	5.95	7.32	8.63	9.30
	(c)	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04
1250	(b)	−4.0	−1.6	0.00	1.82	3.32	4.73	6.17	7.60	8.90	10.9
	(c)	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.05	0.07
1700	(b)	−4.0	−1.6	0.00	3.54	4.89	6.33	7.83	9.72	11.9	12.8
	(c)	0.01	0.01	0.01	0.03	0.04	0.05	0.06	0.08	0.11	0.14
2300	(b)	−4.0	−1.6	0.00	0.73	2.30	5.25	6.71	9.89	12.6	14.8
	(c)	0.01	0.01	0.01	0.01	0.03	0.05	0.05	0.09	0.15	0.18
2900	(b)	−4.0	−1.6	0.00	0.79	2.45	5.60	6.97	9.85	11.4	14.8
	(c)	0.01	0.01	0.01	0.01	0.03	0.06	0.07	0.11	0.14	0.20
3500	(b)	−4.0	−1.6	0.00	0.74	2.49	7.06	8.59	10.5	11.7	15.0
	(c)	0.01	0.01	0.01	0.02	0.03	0.08	0.10	0.13	0.18	0.32
4200	(b)	−4.0	−1.6	0.00	2.43	3.89	5.38	6.91	9.85	13.0	14.6
	(c)	0.01	0.01	0.01	0.04	0.05	0.07	0.09	0.13	0.26	0.33
5100	(b)	−4.0	−1.6	0.00	3.64	5.10	6.63	8.06	11.2	12.5	14.6
	(c)	0.01	0.02	0.02	0.06	0.08	0.09	0.11	0.22	0.29	0.35
6000	(b)	−4.0	−1.6	0.00	2.76	4.18	5.53	6.94	10.9	12.1	13.1
	(c)	0.02	0.02	0.02	0.06	0.09	0.10	0.12	0.26	0.33	0.39

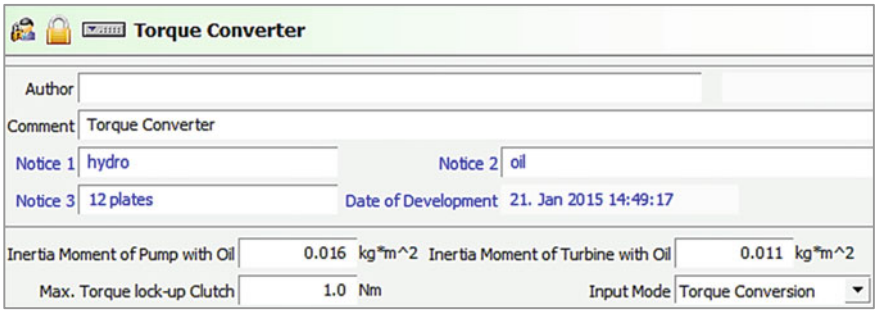


Fig. 4.12 Torque Converter input data specifications window

The Efficiency Fixed curve can be defined as function of the transmission ratio (Fig. 4.15). The additional torque loss correction fixed curve is defined as function of the transmission ratio and the drive speed (Fig. 4.16).

Final Drive (5) is a gear step with fixed ratio. It can be used as a transmission step of the differential (final drive unit). A drive torque will be transferred to a power take-off torque of the transmission step by considering the transmission, the mass moments of inertia, and the moment of loss (Fig. 4.17) [2]. To define

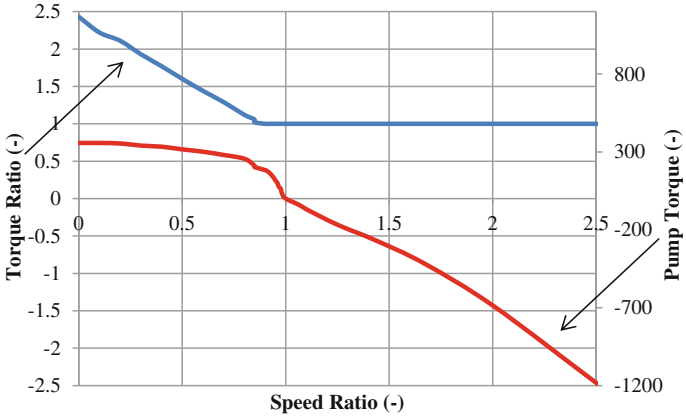


Fig. 4.13 Torque conversion curve

Table 4.11 Torque conversion curve data

Speed Ratio (–)	Torque Ratio (–)	Pump Torque (–)	Speed Ratio (–)	Torque Ratio (–)	Pump Torque (–)
0.000	2.430	357	0.975	1.000	65
0.100	2.220	357	0.980	1.000	40
0.200	2.110	354	0.985	1.000	24
0.300	1.930	340	0.989	1.000	12
0.400	1.770	333	1.000	1.000	0
0.500	1.600	316	1.019	1.000	−13
0.600	1.440	301	1.021	1.000	−15
0.700	1.290	280	1.027	1.000	−18
0.800	1.120	256	1.032	1.000	−20
0.848	1.060	213	1.043	1.000	−27
0.850	1.020	202	1.065	1.000	−41
0.900	1.000	183	1.088	1.000	−59
0.920	1.000	167	1.112	1.000	−77
0.940	1.000	137	1.252	1.000	−169
0.950	1.000	117	1.431	1.000	−266
0.960	1.000	99	1.669	1.000	−416
0.965	1.000	80	2.004	1.000	−689
0.970	1.000	72	2.506	1.000	−1188

component input data double click on the Single Ratio Transmission icon and enter the following data (Table 4.14).

The **Wheels** and **Tires** link the vehicle to the road. The wheel components take into consideration many influencing variables and their effect on the rolling state (Fig. 4.18).

Table 4.12 Torque Converter input data

Name	Value	Unit
Inertia Moment of Pump with Oil	0.016	kg m^2
Max. Torque lock-up Clutch	1.0	Nm
Inertia Moment of Turbine with Oil	0.011	kg m^2
Input Mode	Torque Conversion	–

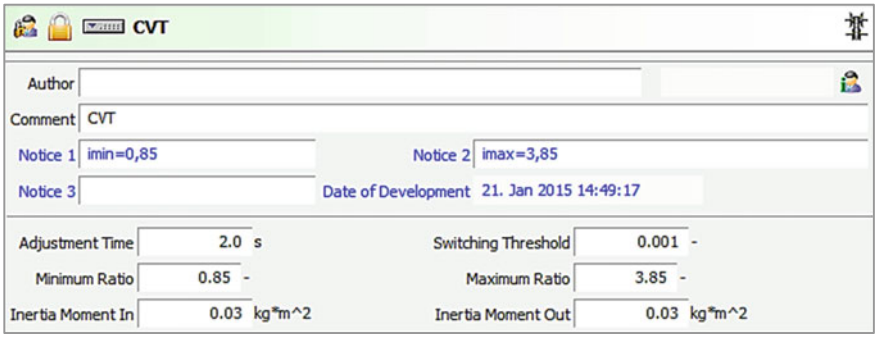


Fig. 4.14 CVT input data specifications window

Table 4.13 CVT input data

Name	Value	Unit
Adjustment Time	2.00	s
Minimum Ratio	0.85	–
Inertia Moment In	0.03	kg m^2
Switching Threshold	0.001	–
Maximum Ratio	3.85	–
Inertia Moment Out	0.03	kg m^2

The moment of rolling drag can be computed on the basis of the wheel load, the corrected dynamic rolling radius, and the coefficient of rolling drag.

The longitudinal tire force results from the friction coefficient, the wheel load as well as from the wheel load factor and the slip factor. It is possible to define variable friction coefficients along the driving profile when different road conditions are considered [2].

Information data for the four wheels are the same (Vehicle Front Right (6), Vehicle Rear Right (7), Vehicle Front Left (8), and Vehicle Rear Left (9)).

Double click on the wheel and enter the following data (Table 4.15). Select Properties menu and define the appropriate wheel location for each wheel (Vehicle: Front Right, Rear Right, Front Left, and Rear Left) [1].

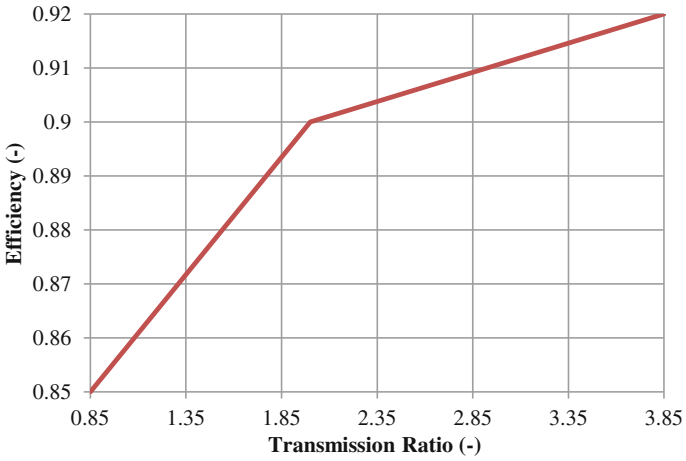


Fig. 4.15 Efficiency

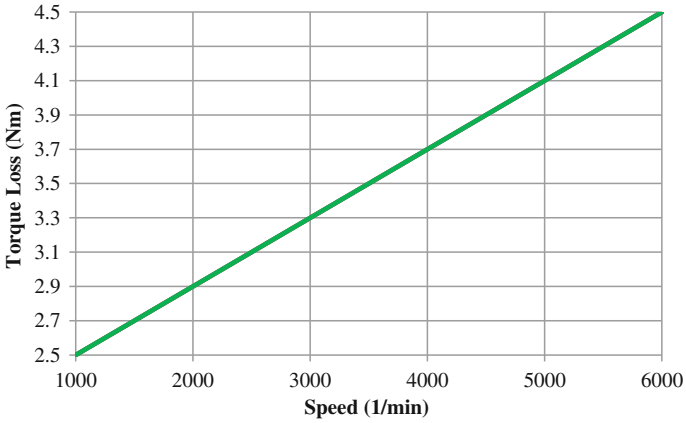


Fig. 4.16 Torque loss correction fixed

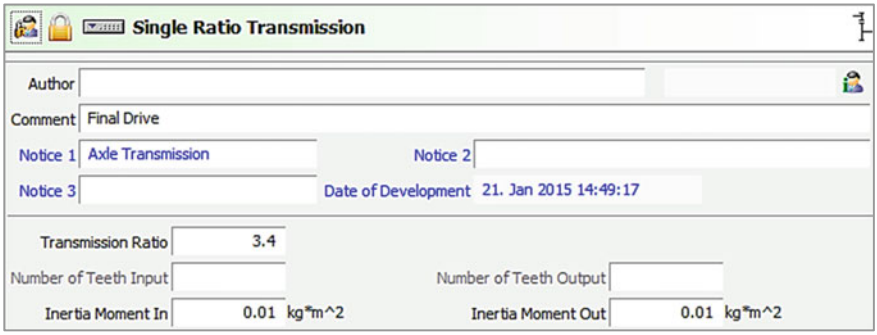


Fig. 4.17 Final Drive input data specifications window

Table 4.14 Final Drive input data

Name	Value	Unit
Transmission Ratio	3.40	–
Inertia Moment In	0.01	kg m^2
Inertia Moment Out	0.01	kg m^2
Efficiency	0.95	–

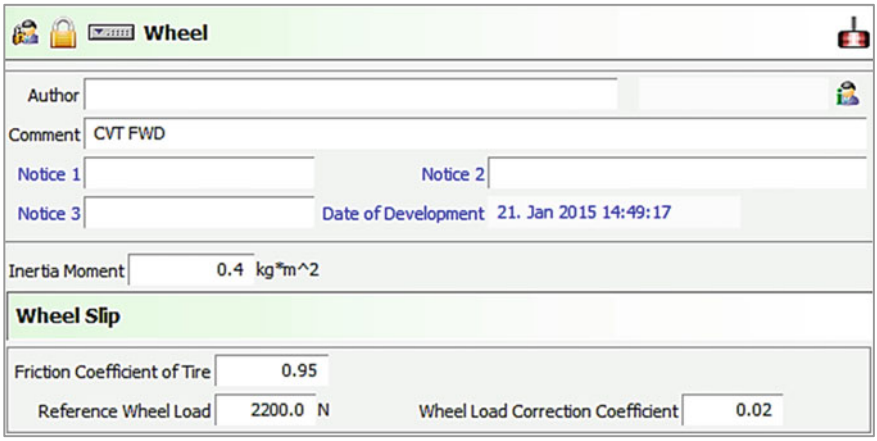


Fig. 4.18 Wheels input data specifications window

Table 4.15 Wheel input data

Name	Value	Unit
Wheel Inertia Moment	0.40	kg m^2
Friction Coefficient of Tire	0.95	–
Reference Wheel Load	2200.0	N
Wheel Load Correction Coefficient	0.02	–
Static Rolling Radius	250.0	mm
Circumference	1570.80	mm
Dynamic Rolling Radius	260.0	mm
Circumference	1633.63	mm

The static rolling radius is the distance between the center of the wheel and the road surface for the loaded, not moving vehicle. The static rolling radius is not used for AVL CRUISE calculation, but only for the Kinematic Chain Browser.

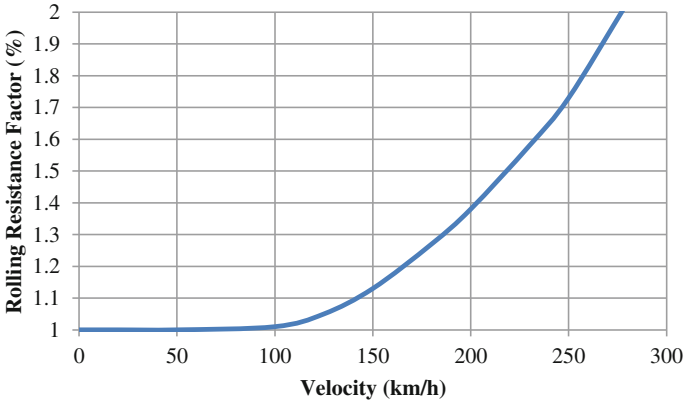


Fig. 4.19 Rolling resistance factor

Table 4.16 Rolling resistance factor data

Velocity (km/h)	Rolling Resistance Factor (%)	Velocity (km/h)	Rolling Resistance Factor (%)
0	1.00	160	1.21
20	1.00	180	1.27
50	1.00	200	1.38
100	1.01	230	1.58
125	1.05	250	1.73
150	1.13	280	2.03

The dynamic rolling radius is the distance between the center of the wheel and the road surface for the loaded, moving vehicle. The dynamic rolling radius is usually a little bit bigger than the static rolling radius.

The dynamic rolling radius can be defined as function of the velocity (Fig. 4.19 and Table 4.16). This characteristic is active when dynamic rolling radius is set from characteristic (a—velocity (km/h), b—rolling resistance factors (%)).

The **Brake** component is described by brake data and dimensions. It is possible to define drum brakes as well as disk brakes. The retarder is used for heavy vehicles and is described below (Fig. 4.20).

The braking torque is computed considering the braking dimensions and the input brake pressure. This brake pressure can come from the cockpit component or brake control. If the vehicle is standing still, the degrees of freedom will be reduced as this also reduces the calculation time. This reduction is done in a way that the equation system is switched if a small velocity threshold is reached. In this case movement is suppressed [2].

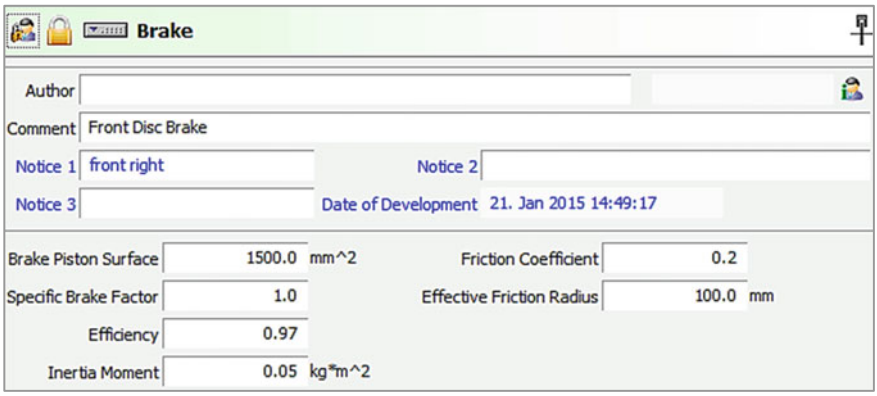


Fig. 4.20 Brake input data specifications window

Table 4.17 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	1500.0	500.0	1500.0	500.0	mm^2
Specific Factor	1.00	3.00	1.00	3.00	–
Efficiency	0.97	0.97	0.97	0.97	–
Inertia Moment	0.05	0.05	0.05	0.05	$kg\ m^2$
Friction Coefficient	0.20	0.20	0.20	0.20	–
Friction Radius	100	90	100	90	mm

At the same time, the instantaneous compulsive force is checked (if it is smaller than the braking torque). If this condition is no longer true the brake is released.

Input data for the two front brakes are the same and also the data for the two rear brakes are the same (Front Disk Brake Right (10), Rear Drum Brake Right (11), Front Disk Brake Left (12) and Rear Drum Brake Left (13)). Double click on the brake icon and enter the following data (Table 4.17).

Differential (14) unit compensates for discrepancies in the respective rotation rates of the drive wheels: between inside and outside wheels during cornering and between different drive axles on 4WD vehicles (Fig. 4.21).

When there is a unilateral variation in road surfaces it results in different coefficients of friction at the respective wheels, this balance effect limits the effective drive torque to a level defined as twice the traction force available at the wheel (tire) with the lower friction coefficient [2].

This wheel then responds to the excessive force by spinning. To avoid such effects a positive lock is available at the component.

In the differential it is possible to define the torque split factor. This is needed if it is used as a central differential for a four wheel drive.

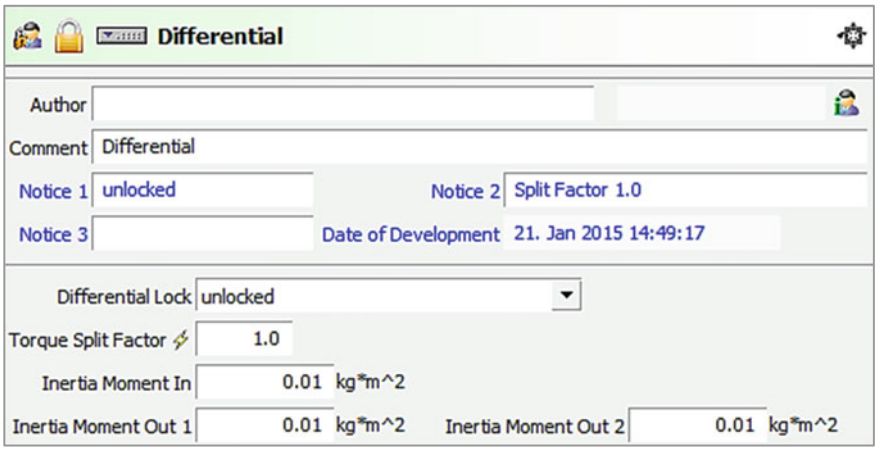


Fig. 4.21 Differential input data specifications window

Table 4.18 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.00	–
Inertia Moment In	0.01	kg m^2
Inertia Moment Out1	0.01	kg m^2
Inertia Moment Out2	0.01	kg m^2

To define component input data double click on the differential icon and enter the following data (Table 4.18).

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component (Fig. 4.22). All mechanical connections starting from the selected component are shown in a tree structure on the left side of the window. When a second component is selected in the tree structure, all speeds between the selected components are shown in the table on the right side of the window, each row representing one gear of the gearbox [2].

Cockpit (15) links the driver and the vehicle (Fig. 4.23). In this component connections are only made via Data Bus.

The driver gets information such as vehicle velocity and vehicle acceleration, but also generates information such as the pedal positions for other components. The pedal positions are transferred to corresponding indicators via the pedal characteristics (Table 4.19) [2].

To define the input data click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)) and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data (Fig. 4.24).

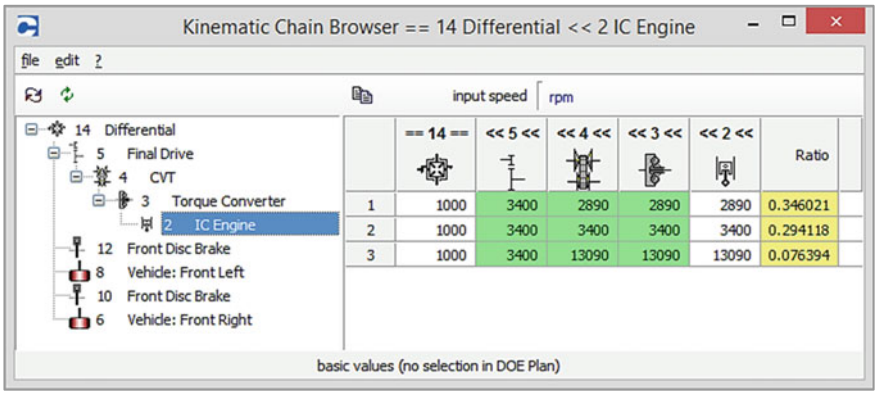


Fig. 4.22 Kinematic Chain Browser

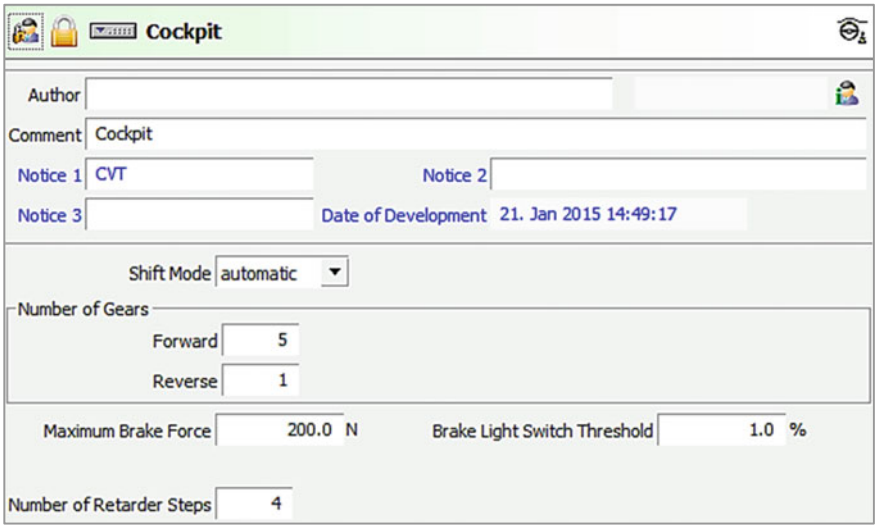


Fig. 4.23 Cockpit input data specifications window

Table 4.19 Cockpit input data

Name	Value	Unit
Shift Mode	Automatic	–
Number of Gears Forward	5	–
Number of Gears Back	1	–
Maximum Brake Force	200.0	N
Brake Light Switch Threshold	1.0	%
Number of Retarder Steps	4	–

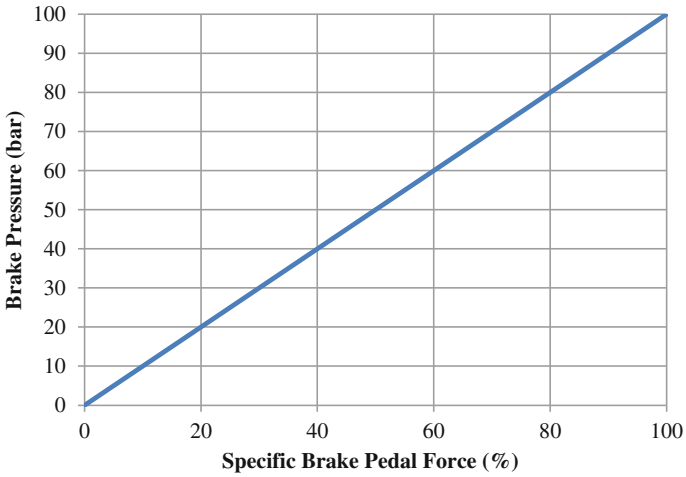


Fig. 4.24 Pedal characteristic

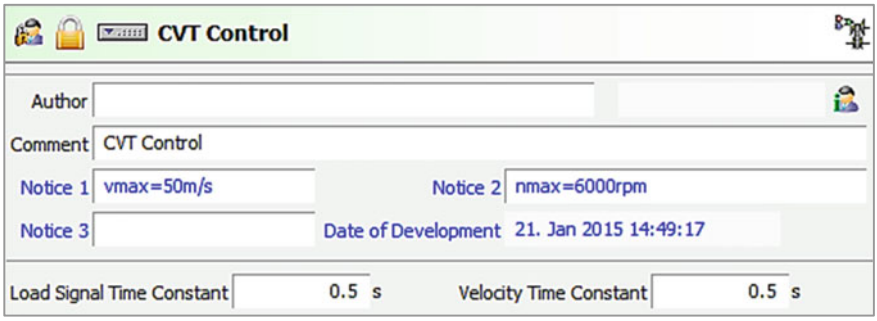


Fig. 4.25 CVT control input data specifications window

Table 4.20 CVT control input data

Name	Value	Unit
Maximum Velocity	50.00	m/s
Maximum Speed	6000	1/min
Load Signal Time Constant	0.50	s
Velocity Time Constant	0.50	s

The **CVT Control** (16) is an easy way to provide target transmission considering the velocity and the engine load. In addition, it is possible to control the clutch. This clutch is simply added to the model (Fig. 4.25).

To define component input data double click on the CVT control icon and enter the following data (Table 4.20).

Table 4.21 Desired transmission ratio data

(a)												
0	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
5	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	2.7	2.9	3.0	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
10	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	1.4	1.6	1.8	1.9	2.0	2.1	2.2	2.4	2.7	3.1	3.8
15	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.8	2.3	2.8
20	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	1.0	1.0	1.0	1.1	1.2	1.5	1.8	2.1
25	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.2	1.4	1.7
30	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.2	1.4
35	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.1	1.2
40	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.1
45	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0
50	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

To define the input data for desired transmission ratio click on the tabs and enter the following data (Table 4.21 and Fig. 4.26). The demand transmission of the CVT gearbox can be defined as a function of a—velocity (m/s), b—load signal (%) and c—transmission ratio (–). The interpolation of transmission ratio in the maps of CVT control are done by an alternative method and can be changed in the interpolation and approximation section in the Expert Mode settings of the Project Settings [3].

To define the input data for desired clutch release click on the tabs and enter the following data (Fig. 4.27 and Table 4.22). The demand clutch release of the starting clutch can be defined as a function of a—speed (1/min), b—load signal (%) and c—clutch release (%) [3].

The **ASC Anti-Slip Control** (17) checks the force transmission factor (ratio between force that should be transmitted and maximum transmittable force) of all connected wheels (driven wheels). If the force that has to be transmitted exceeds the adhesion limit, the load signal or the clutch releases changes [2].

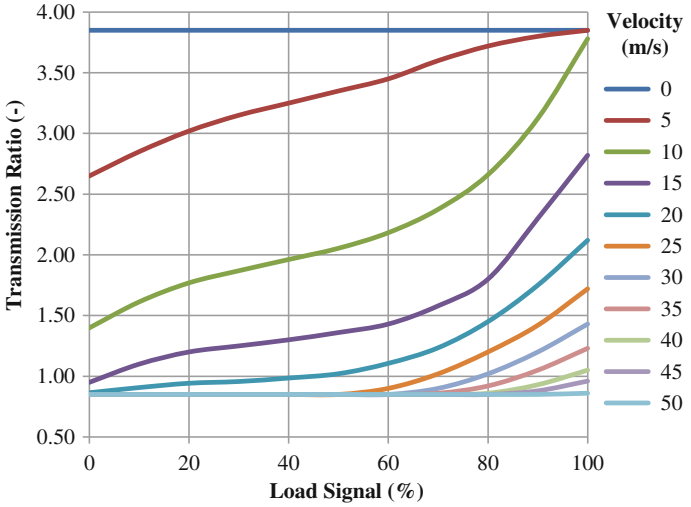
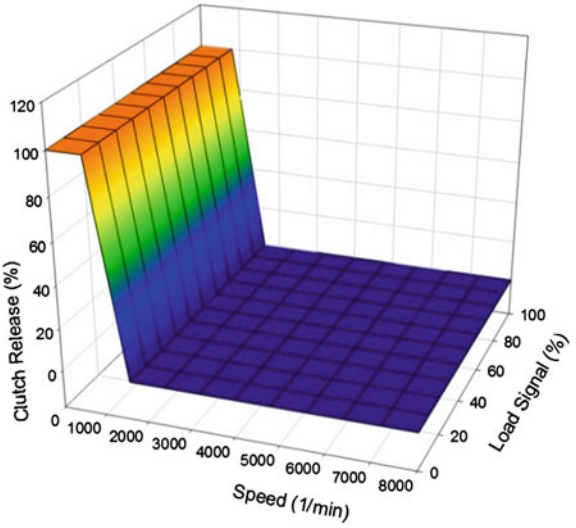


Fig. 4.26 Desired transmission ratio

Fig. 4.27 Desired clutch release



The Anti-Slip Control (Fig. 4.28) is only active when a model is calculated quasi-stationary in combination with special drivetrain configurations and does not require data entry.

If the Anti-Slip Control is used for calculations in simulation mode this switch can be activated. In this case the parameters for the PID controller can be set (proportional (–), differential (s) and integral parameter (1/s)).

Table 4.22 Desired clutch release data

(a)												
0	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	100	100	100	100	100	100	100	100	100	100	100
800	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	100	100	100	100	100	100	100	100	100	100	100
1600	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
2400	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
3200	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
4000	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
4800	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
5600	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
6400	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
7200	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0
8000	(b)	0	10	20	30	40	50	60	70	80	90	100
	(c)	0	0	0	0	0	0	0	0	0	0	0

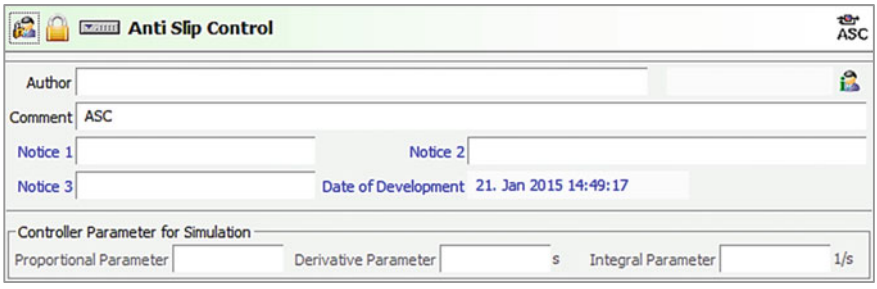


Fig. 4.28 ASC Anti-Slip Control input data specifications window

Catalyst (18) or exhaust systems consider the effects of the catalytic converter and soot filler on the raw emissions of the engine.

Starting with the temperature of the catalytic converter, factors for the conversion will be computed for the single emission components using temperature-dependent maps (Fig. 4.29).

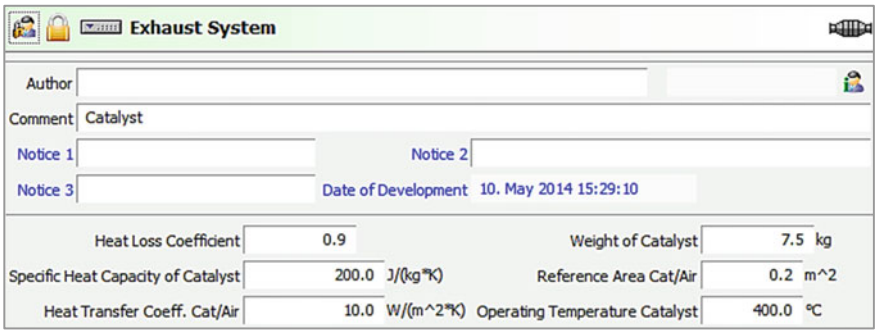


Fig. 4.29 Catalyst input data specifications window

Table 4.23 Catalyst input data

Name	Value	Unit
Heat Loss Coefficient	0.90	–
Weight of Catalyst	7.50	kg
Specific Heat Capacity of Catalyst	200.0	J/kg K
Reference Area Cat/Air	0.20	m^2
Heat Transfer Coefficient Cat/Air	10.0	W/m^2 K
Operating Temperature Catalyst	400.0	°C

The heat loss coefficient is the percentage of the exhaust energy delivered by the engine which reaches the exhaust system [2].

To define component input data double click on the catalyst icon and enter the following data (Table 4.23).

Conversion efficiencies of the different emissions (NO_x, CO, HC and Soot) can be defined dependent on the actual temperature of the catalytic converter.

Conversion efficiencies curve can be defined as function of a—temperature (°C) and efficiency (–) (Table 4.24 and Fig. 4.30—NO_x conversion efficiencies, Table 4.25 and Fig. 4.31—CO conversion efficiencies, Table 4.26 and Fig. 4.32—HC conversion efficiencies).

The heat transfer Gas/Cat (Table 4.27 and Fig. 4.33) is the proportion of the exhaust gas which is transferred to the exhaust system and can be defined as a function of a—temperature (°C) and b—heat-up proportion of exhaust gas energy (%) [1].

The **Monitor** (19) can be introduced, if the calculation run must be detected. It is possible to show some results of the calculation while the calculation is running. This is done via the online monitor. It is possible to connect up to ten input channels of the monitor to output channels of different components that are available at the AVL CRUISE—Data Bus [2].

Table 4.24 NO_x conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

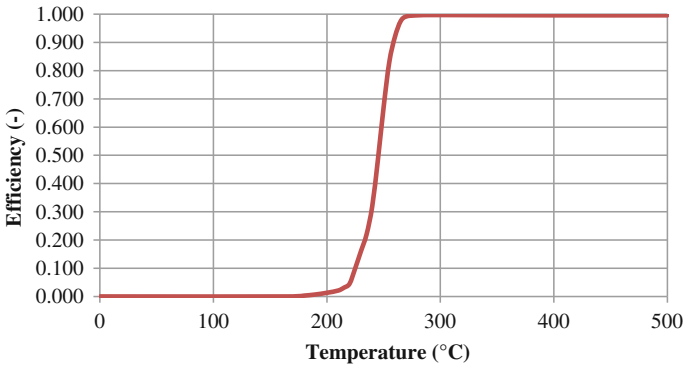


Fig. 4.30 NO_x conversion efficiency

Table 4.25 CO conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

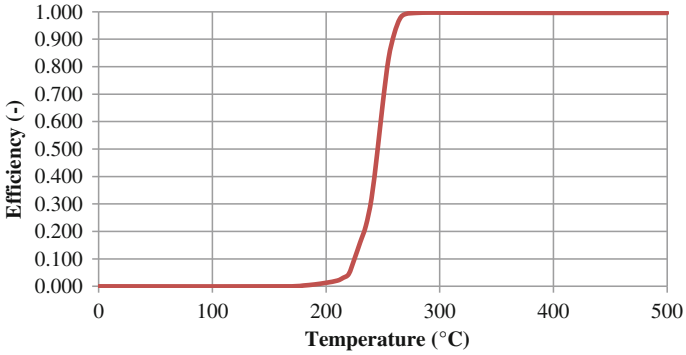


Fig. 4.31 CO conversion efficiency

Table 4.26 HC conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

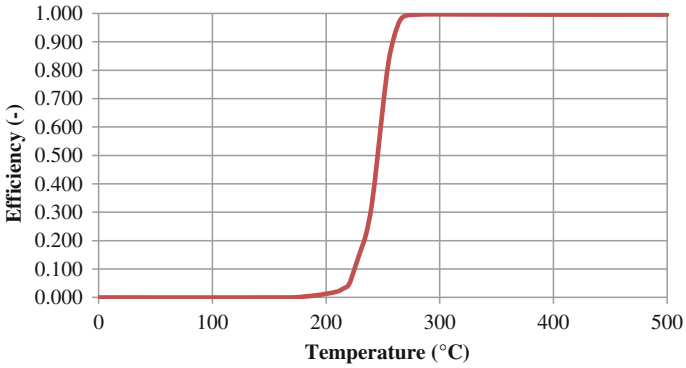


Fig. 4.32 HC conversion efficiency

Table 4.27 Heat transfer Gas/Cat data

Temperature (°C)	Heat-Up Proportion of Exhaust Gas Energy (%)
–30	41
210	39
270	65
500	64
600	64
1000	64

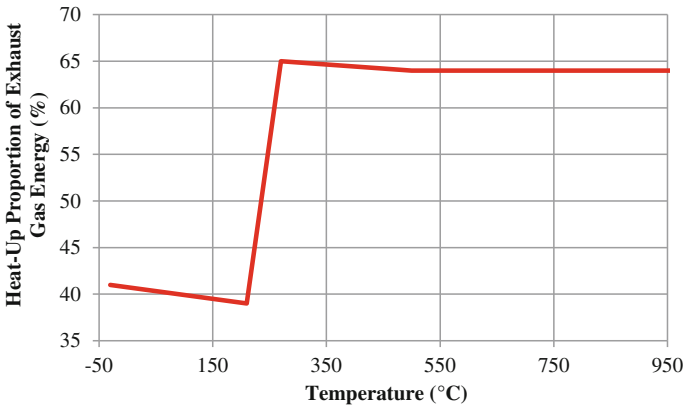


Fig. 4.33 Heat transfer Gas/Cat

Currently, the output in the online monitor is only available in the form of tables. More than one monitor component can be used in a AVL CRUISE model. In this case, more than one instance of the online monitor is activated during calculation.

Click on the description of Data Bus tab and open the following dialog. To select a Data Bus channel, click to access the available list. Enter the text for the description and then click on to select the unit (Fig. 4.34).

4.1.2 Automatic FWD Model

This chapter describes how to create and run the model of an automatic front wheel drive vehicle. To place a component in the working area, click on the component group with the left mouse button, move the mouse over the required component and then click and drag the component into the vehicle model area. Put the component with release of the mouse button on the desired place.

Place the following components in the working area: Vehicle (1), IC Engine (2), Torque Converter (3), Gearbox (4), Final Drive (5), Vehicle Front Right (6),

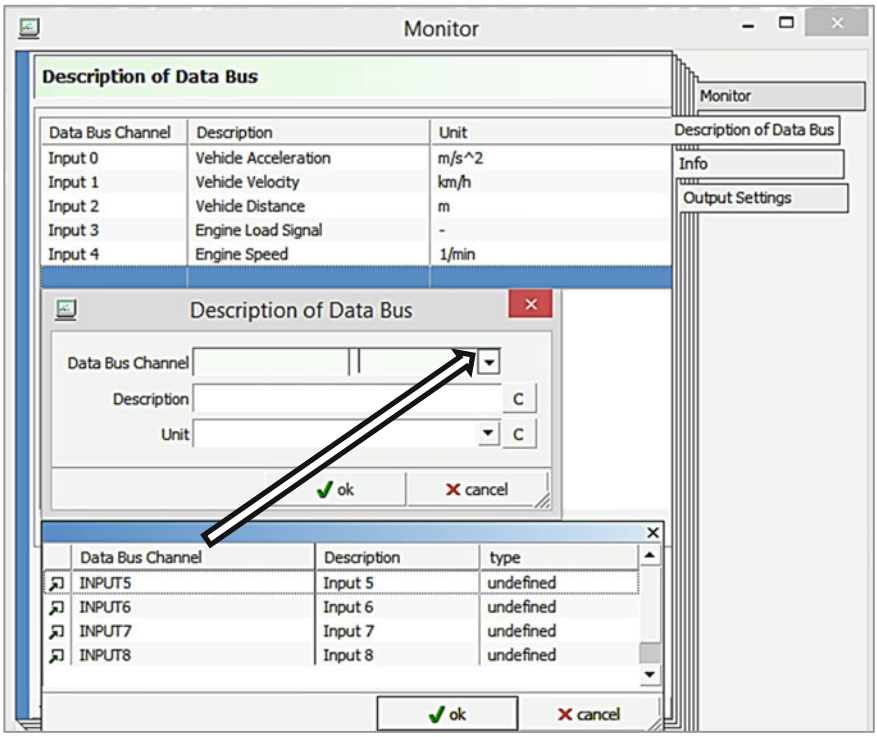


Fig. 4.34 Monitor description of Data Bus

Vehicle Rear Right (7), Vehicle Front Left (8), Vehicle Rear Left (9), Front Disk Brake (10), Rear Drum Brake (11), Front Disk Brake (12), Rear Drum Brake (13), Differential (14), Cockpit (15), Gearbox control (16), Gearbox program (17), ASC Anti-Slip Control (18), Catalyst (19) and Monitor (20).

Arrange the components as shown in Fig. 4.35 and connect the components as specified in the diagram.

The electric connections for energy transfer are splinted as a function of energy that is transferred into mechanical, for exhaust gases and electrical connections. The links between elements are specified in red, green, or blue, depending on their type.

All the connections in the Data Bus for this model are described in Table 4.28 [1]. Validation of the connections marked in bold are required for functioning of the model.

The **Vehicle** (1) is one of the main objects in a model. This component contains general data of the vehicle, such as nominal dimensions and weights. Only one vehicle component is required in a model.

Road resistances and dynamic wheel loads are calculated for road and dynamometer runs based on the dimensions and the load state. The wheel loads are

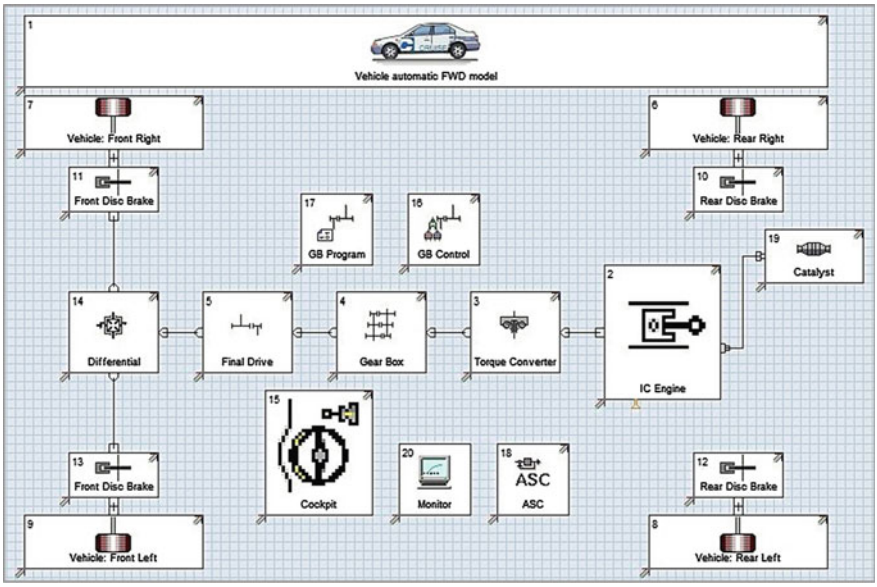


Fig. 4.35 Complete model automatic FWD

calculated considering motion. The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated [2].

To define component input data (Table 4.29) double click on the icon and select edit to open the following window (Fig. 4.36).

IC Engine (2) component contains a model for a combustion engine. The characteristic curves for the full load, the fuel consumption, and others can be freely defined by the user [2].

To define component input data (Table 4.30) double click on the icon and select edit to open the following window (Fig. 4.37).

To load IC Engine characteristic click on the Full Load Characteristic tab (Table 4.31 and Fig. 4.38). Select a—speed (1/min) and b—power (kW) by pull-down menu and enter the following data.

The Motoring Curve (Table 4.32 and Fig. 4.39) will be defined similar to the Full Load Characteristic as power versus engine speed [1].

Fuel Consumption Map (Table 4.33 and Fig. 4.40) shows the actual fuel consumption for stationary operation (a—speed (1/min), b—BMEP (bar), c—volume flow (l/h)).

In the emission maps the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—mass flow (kg/h), namely NO_x emission map in Fig. 4.41 and Table 4.34, CO emission map in Fig. 4.42 and Table 4.35, HC emission map in Fig. 4.43 and Table 4.36 [1].

Table 4.28 All the Data Bus connection

Component Requires	Input Information	Component Delivering	Output Information
ASC	**Load Signal**	Cockpit	Load Signal
	Slip Front Left	Wheel Front Left	Slip Signal
	Slip Front Right	Wheel Front Right	Slip Signal
Brake Front Disk	**Brake Pressure**	Cockpit	Brake Pressure
Brake Rear Drum	**Brake Pressure**	Cockpit	Brake Pressure
Brake Front Disk	**Brake Pressure**	Cockpit	Brake Pressure
Brake Rear Drum	**Brake Pressure**	Cockpit	Brake Pressure
Cockpit	**Gear Indicator**	Gear Box	Current Gear
	Operation Control 0	IC Engine	Operation Control
	Speed	Engine Speed	Speed
Differential	–	–	–
IC Engine	**Load Signal**	ASC	Load Signal
	Start Switch	Cockpit	Start Switch
Gearbox	**Desired Gear**	Gearbox Control	Desired Gear
Gearbox Control	**Current Gear**	Gearbox	Current Gear
	Desired Gear Cockpit	Cockpit	Desired Gear
	Desired Gear GB	Gearbox Program	Desired Gear
	Gear Downshifting	Cockpit	Gear Downshifting
	Gear Upshifting	Cockpit	Gear Upshifting
	Operation Control	Cockpit	Operation Control
	Reference Speed	Torque Converter	Turbine Speed
	Velocity	Cockpit	Velocity
Gearbox Program	**Current Gear**	Gearbox	Current Gear
	Load Signal	Cockpit	Load Signal
	Speed	Gearbox	Output Speed
Monitor	Vehicle Acceleration	Vehicle Automatic	Acceleration
	Vehicle Velocity	Vehicle Automatic	Velocity
	Vehicle Distance	Vehicle Automatic	Distance
	Engine Load Signal	IC Engine	Actual Load Signal
	Engine Speed	IC Engine	Engine Speed

Torque Converter (3) employs the force represented by a moving fluid to transmit engine torque (Fig. 4.44). As these devices compensate for differences in the rotating speeds of engine and drivetrain, they are ideal for effecting the transition from stationary to mobile operation [2].

To define component input data (Table 4.37) double click on the icon and select edit to open the following window. The torque on the converter input and output depends on the speed ration between pump and turbine as well as on the absolute

Table 4.29 Vehicle component input data

Name	Value	Unit
Gas Tank Volume	0.070	m^3
Distance from Hitch to Front Axle	3200.0	mm
Height of Support Point at Bench Test	100.0	mm
Wheel Base	2500.0	mm
Distance of Gravity Center empty/half/full	1200.0/1210.0/1220.0	mm
Height of Gravity Center empty/half/full	550.0/540.0/530.0	mm
Height of Hitch empty/half/full	400.0/380.0/360.0	mm
Tire Inflation Pressure Front Axle	2.200	bar
Tire Inflation Pressure Rear Axle	2.200	bar
Curb Weight	1450.0	kg
Gross Weight	1890.0	kg
Frontal Area	2.000	m^2
Drag Coefficient	0.400	–

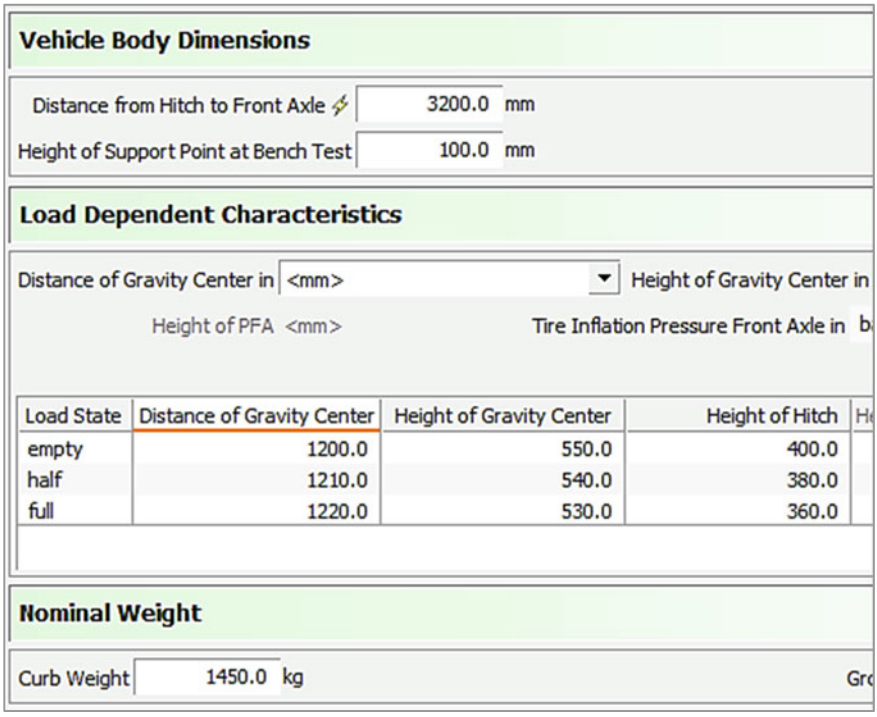


Fig. 4.36 Vehicle input data specifications window

Table 4.30 IC Engine component input data

Name	Value	Unit
Engine Displacement	1998.0	cm^3
Engine Working Temperature	80.00	°C
Number of Cylinders	4.000	–
Number of Strokes	4.000	–
Idle Speed	800.0	1/min
Maximum Speed	6000.0	1/min
Inertia Moment	0.150	kg m^2
Response Time	0.100	s
Heating Value for Gasoline	44500.0	kJ/kg
Fuel Density	0.737	kg/l
Idle Consumption	1.500	l/h
Idle Emission NO_x	0.030	kg/h
Idle Emission CO	0.150	kg/h
Idle Emission HC	0.015	kg/h
Residual Fuel Consumption	0.000	l/h
Lower Speed for Fuel Shut-Off	1000.0	1/min
Upper Speed for Fuel Shut-Off	1200.0	1/min

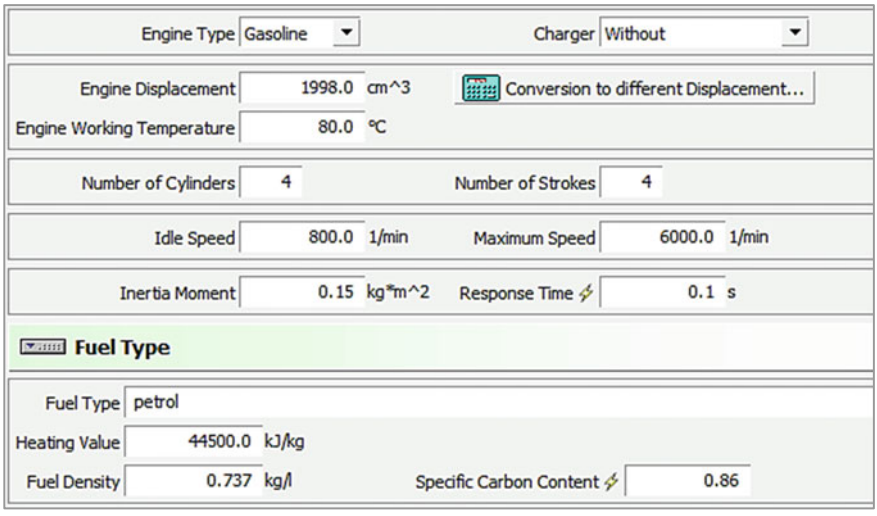


Fig. 4.37 IC Engine input data specifications window

angular velocity of the pump (a—speed ratio (–), b—torque ratio (–), c—pump torque (–), Fig. 4.45 and Table 4.38).

Gearbox (4) transmissions featuring several fixed ratios can maintain a correspondence between the respective performance curves for engine and vehicle

Table 4.31 Full Load Characteristic data

Speed (1/min)	Power (kW)	Speed (1/min)	Power (kW)
800	9	3900	95
1300	25	4300	104
1800	37	4800	117
2100	46	5200	124
2500	57	5600	127
3000	69	5800	126
3250	76	6000	125
3500	84	–	–

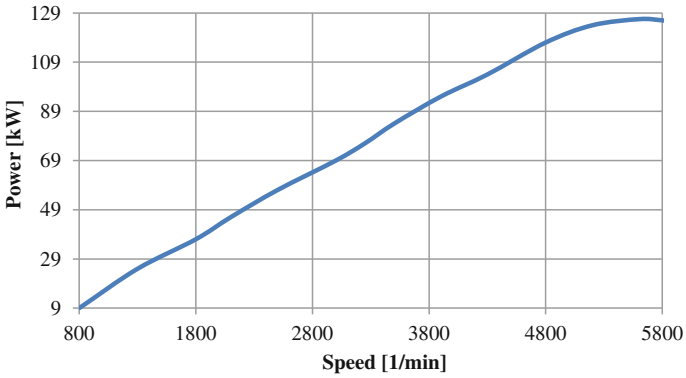


Fig. 4.38 Full Load Characteristic

Table 4.32 Motoring Curve data

Speed (1/min)	Power (kW)	Speed (1/min)	Power (kW)
800	0.0	3900	−11.0
1400	−3.0	4500	−12.0
2000	−5.5	5200	−13.0
2600	−7.5	6000	−14.0
3300	−9.5	3900	−11.0
800	0.0	4500	−12.0
1400	−3.0	–	–

(Fig. 4.46). The correspondence with the hyperbola for maximum engine output will be acceptable or indeed quite good, depending on a multiplicity of factors including the number of available gears, the spacing of the individual ratios within the required conversion range, and the engines' full-load torque curve [2].

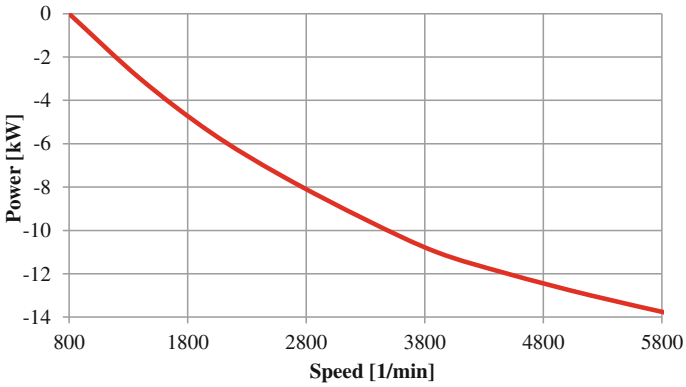


Fig. 4.39 Motoring Curve

Table 4.33 Fuel Consumption Map data

(a)											
700	(b)	−4.0	−0.5	0.0	1.60	3.16	4.55	5.95	7.32	8.63	9.30
	(c)	1.60	1.61	1.65	1.88	2.13	2.50	2.96	3.55	4.19	4.79
1200	(b)	−4.0	−0.5	0.0	0.35	1.82	3.32	6.17	7.59	8.90	10.9
	(c)	1.75	1.76	1.80	1.93	2.35	2.78	4.25	4.97	5.87	6.72
1700	(b)	−4.0	−0.5	0.0	0.42	2.06	3.54	6.33	9.48	10.9	12.3
	(c)	1.95	1.96	2.00	2.16	2.85	3.72	5.53	7.70	9.43	10.6
2550	(b)	−4.0	−0.5	0.0	0.73	2.30	3.80	6.71	9.55	12.4	14.3
	(c)	2.25	2.30	2.45	2.98	4.20	5.69	8.30	10.9	15.1	17.6
3000	(b)	−4.0	−0.5	0.0	0.71	2.42	3.97	6.97	8.41	11.3	14.8
	(c)	2.73	2.84	3.00	3.55	5.21	6.85	10.0	11.5	14.8	20.9
3600	(b)	−4.0	−0.5	0.0	0.72	2.41	3.97	7.04	10.3	14.7	15.1
	(c)	3.22	3.34	3.67	4.44	6.40	8.47	12.2	16.6	24.8	25.4
4150	(b)	−4.0	−0.5	0.0	0.70	2.31	3.82	5.34	8.53	13.1	15.1
	(c)	4.15	4.27	4.64	5.41	7.66	9.96	12.2	17.0	26.8	33.0
5050	(b)	−4.0	−0.5	0.0	1.99	3.62	5.10	8.12	11.2	12.5	14.5
	(c)	5.25	5.60	6.00	9.43	12.3	14.9	20.7	28.4	33.5	41.8
6000	(b)	−4.0	−0.5	0.0	1.21	2.76	4.18	6.94	9.72	12.1	13.1
	(c)	6.60	7.25	8.00	10.4	13.9	17.1	23.9	34.0	44.7	49.0

The component Gearbox contains a model for a gear box with different gear steps. The user can define as many gears as needed. When it is used as an automatic gearbox, the gear shifting process will be controlled by the control module gearbox control and program. To define component input data for Gear Ratio Table double click on the icon and select edit to open the following window [1].

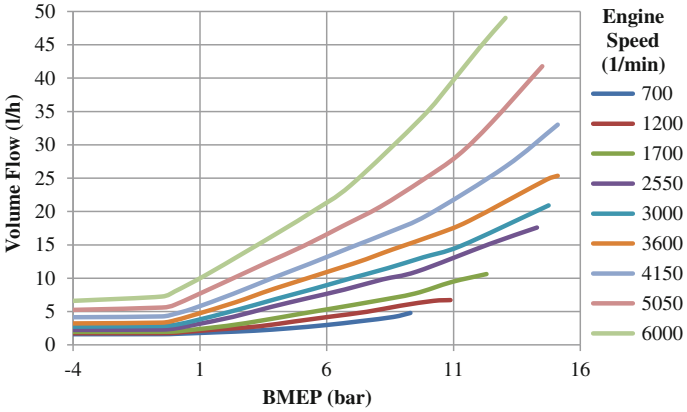


Fig. 4.40 Fuel Consumption Map

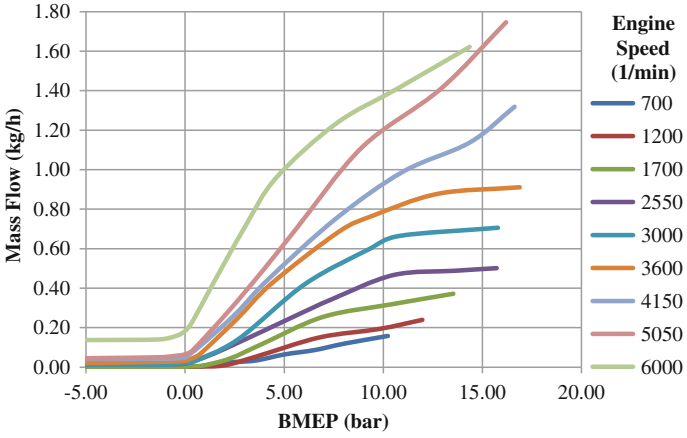


Fig. 4.41 NO_x emission map

The efficiency and torque loss correction can be defined as function of the gear efficiency (Fig. 4.47).

Final Drive (5) is a gear step with fixed ratio (Fig. 4.48). It can be used as a transmission step of the differential (final drive unit). A drive torque will be transferred to a power take-off torque of the transmission step by considering the transmission, the mass moments of inertia and the moment of loss [2].

To define component input data double click on the final drive icon and enter the following data (Table 4.39).

The **Wheels** and **Tires** link the vehicle to the road. The wheel component considers many influencing variables and their effect on the rolling state.

Table 4.34 NO_x emission map data

(a)											
700	(b)	−5.0	−0.6	0.00	0.90	1.76	3.48	5.01	6.55	8.05	10.2
	(c)	0.00	0.00	0.00	0.01	0.02	0.03	0.06	0.09	0.12	0.16
1200	(b)	−5.0	−0.4	0.00	0.21	0.66	2.00	3.65	6.79	9.79	11.9
	(c)	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.15	0.19	0.24
1700	(b)	−5.0	−0.4	0.00	0.25	0.90	2.27	3.89	6.96	10.4	13.5
	(c)	0.00	0.00	0.00	0.00	0.01	0.04	0.12	0.25	0.32	0.37
2550	(b)	−5.0	−0.5	0.00	0.41	2.00	5.78	7.38	10.5	13.6	15.7
	(c)	0.02	0.02	0.02	0.03	0.09	0.27	0.34	0.47	0.49	0.50
3000	(b)	−5.0	−1.0	−0.4	0.00	0.41	2.66	6.04	9.25	10.8	15.8
	(c)	0.01	0.01	0.02	0.02	0.03	0.14	0.42	0.60	0.66	0.71
3600	(b)	−5.0	−0.4	0.00	0.36	2.65	4.37	7.74	9.45	12.8	16.9
	(c)	0.02	0.03	0.03	0.04	0.25	0.42	0.69	0.77	0.88	0.91
4150	(b)	−5.0	−1.0	−0.4	0.00	0.79	2.54	7.59	10.9	14.4	16.6
	(c)	0.04	0.04	0.04	0.05	0.11	0.27	0.75	0.99	1.14	1.32
5050	(b)	−5.0	−1.3	−0.5	0.00	2.19	3.98	5.61	8.93	12.9	16.2
	(c)	0.05	0.05	0.06	0.07	0.28	0.50	0.70	1.11	1.41	1.75
6000	(b)	−5.0	−1.3	−0.4	0.00	1.33	3.04	4.60	7.63	10.7	14.4
	(c)	0.14	0.14	0.16	0.18	0.41	0.71	0.96	1.23	1.41	1.62

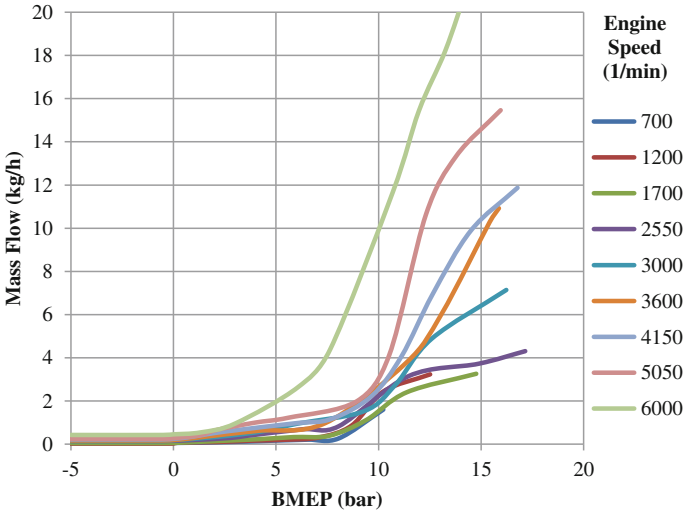


Fig. 4.42 CO emission map

Table 4.35 CO emission map data

(a)											
700	(b)	−5.0	−0.8	0.00	1.76	3.48	5.01	6.55	8.05	10.2	–
	(c)	0.05	0.05	0.06	0.08	0.12	0.17	0.21	0.27	1.60	–
1200	(b)	−5.0	−0.6	0.00	0.22	3.82	5.44	7.10	8.69	10.2	12.5
	(c)	0.03	0.03	0.03	0.07	0.17	0.21	0.31	0.87	2.44	3.23
1700	(b)	−5.0	−0.6	0.00	0.50	4.25	5.87	7.60	9.40	11.4	14.8
	(c)	0.05	0.05	0.06	0.08	0.24	0.33	0.39	1.12	2.41	3.26
2550	(b)	−5.0	−0.6	0.00	0.88	3.60	6.30	8.05	11.5	14.9	17.2
	(c)	0.15	0.15	0.16	0.19	0.39	0.69	0.83	3.15	3.73	4.31
3000	(b)	−5.0	−0.5	0.00	0.78	2.66	6.04	9.29	10.8	12.6	16.2
	(c)	0.15	0.15	0.18	0.23	0.39	0.95	1.53	2.75	4.89	7.14
3600	(b)	−5.0	−0.5	0.00	0.76	4.17	7.39	11.3	13.1	15.4	15.9
	(c)	0.17	0.17	0.19	0.26	0.63	0.97	3.76	6.06	10.3	10.9
4150	(b)	−5.0	−0.6	0.00	0.77	5.93	9.67	11.1	12.6	14.5	16.8
	(c)	0.22	0.22	0.25	0.33	0.97	2.24	4.07	6.92	9.89	11.9
5050	(b)	−5.0	−0.7	0.00	1.23	3.98	5.61	10.5	12.3	13.8	15.9
	(c)	0.25	0.25	0.28	0.41	1.00	1.23	4.12	10.6	13.3	15.5
6000	(b)	−5.0	−0.5	0.00	1.33	6.08	7.63	10.7	11.9	13.3	14.4
	(c)	0.43	0.43	0.46	0.55	2.65	4.38	11.7	15.4	18.2	21.3

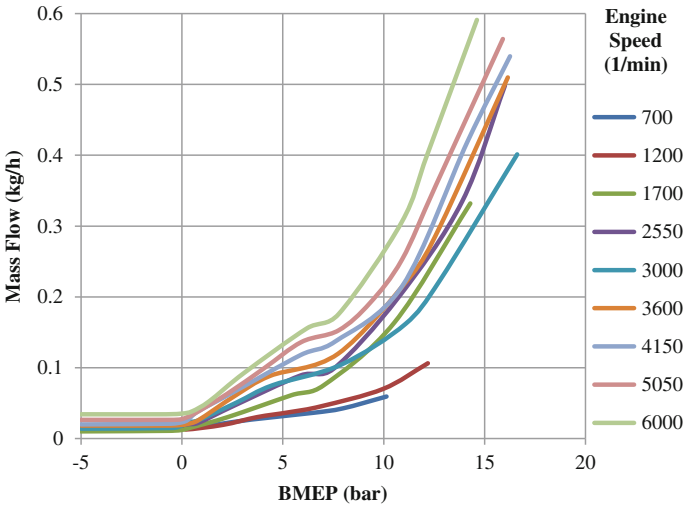


Fig. 4.43 HC emission map

Table 4.36 HC emission map data

(a)											
700	(b)	−5.0	−0.9	0.00	0.66	1.74	3.44	6.49	7.98	10.1	–
	(c)	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.04	0.06	–
1200	(b)	−5.0	−0.6	0.00	0.21	2.04	3.72	5.30	6.91	9.97	12.2
	(c)	0.01	0.01	0.02	0.01	0.02	0.03	0.04	0.05	0.07	0.11
1700	(b)	−5.0	−0.6	0.00	0.47	2.29	5.43	7.03	10.5	14.3	–
	(c)	0.01	0.01	0.01	0.02	0.03	0.06	0.08	0.16	0.33	–
2550	(b)	−5.0	−0.6	0.00	0.33	2.58	5.88	7.52	10.7	13.9	16.0
	(c)	0.02	0.02	0.02	0.02	0.05	0.09	0.10	0.20	0.33	0.50
3000	(b)	−5.0	−0.5	0.00	0.80	2.73	4.49	7.88	11.1	12.8	16.6
	(c)	0.01	0.02	0.02	0.03	0.05	0.08	0.10	0.16	0.22	0.40
3600	(b)	−5.0	−0.6	0.00	0.30	2.65	4.37	7.74	11.3	12.8	16.2
	(c)	0.02	0.02	0.02	0.02	0.06	0.09	0.12	0.23	0.30	0.51
4150	(b)	−5.0	−0.6	0.00	0.30	2.54	5.87	7.59	10.9	14.2	16.3
	(c)	0.02	0.02	0.02	0.03	0.07	0.12	0.14	0.22	0.42	0.54
5050	(b)	−5.0	−0.4	0.00	0.57	2.24	5.93	7.76	9.32	12.6	15.9
	(c)	0.03	0.03	0.03	0.03	0.06	0.14	0.15	0.19	0.36	0.56
6000	(b)	−5.0	−0.8	0.00	0.52	1.36	3.09	7.77	10.9	12.2	14.6
	(c)	0.03	0.03	0.04	0.04	0.05	0.09	0.18	0.31	0.40	0.59

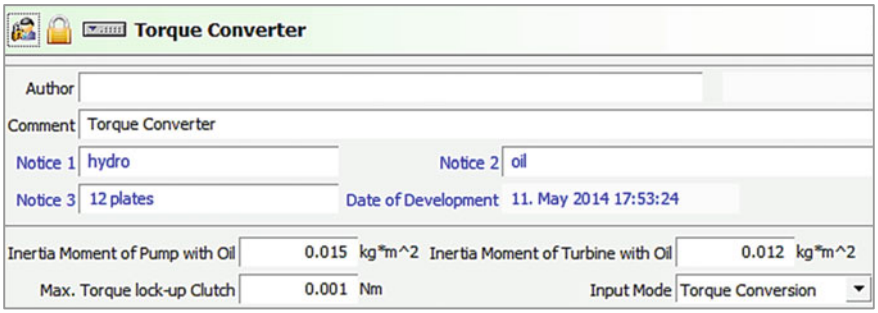


Fig. 4.44 Torque Converter input data specifications window

Information data for the four wheels are the same (Vehicle Rear Right (6), Vehicle Front Right (7), Vehicle Rear Left (8), and Vehicle Front Left (9)).

Double click on the wheel (Fig. 4.49) and enter the following data (Table 4.40). Select Properties menu and define the appropriate wheel location for each wheel (Vehicle: Front Right, Rear Right, Front Left, and Rear Left).

The static rolling radius is the distance between the center of the wheel and the road surface for the loaded, not moving vehicle.

Table 4.37 Torque Converter input data

Name	Value	Unit
Inertia Moment of Pump with Oil	0.015	kg m^2
Max. Torque lock-up Clutch	1.000	Nm
Inertia Moment of Turbine with Oil	0.015	kg m^2
Input Mode	Torque Conversion	–

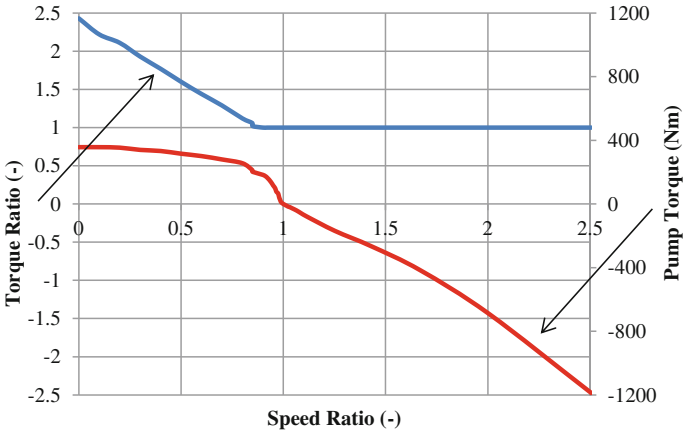


Fig. 4.45 Torque conversion curve

Table 4.38 Torque conversion curve data

Speed Ratio (–)	Torque Ratio (–)	Pump Torque (–)	Speed Ratio (–)	Torque Ratio (–)	Pump Torque (–)
0.000	2.430	0.920	1.000	1.021	1.000
0.100	2.220	0.940	1.000	1.027	1.000
0.200	2.110	0.950	1.000	1.032	1.000
0.300	1.930	0.960	1.000	1.043	1.000
0.400	1.770	0.965	1.000	1.065	1.000
0.500	1.600	0.970	1.000	1.088	1.000
0.600	1.440	0.975	1.000	1.112	1.000
0.700	1.290	0.980	1.000	1.252	1.000
0.800	1.120	0.985	1.000	1.431	1.000
0.848	1.060	0.989	1.000	1.669	1.000
0.850	1.020	1.000	1.000	2.004	1.000
0.900	1.000	1.019	1.000	2.506	1.000

Gear Ratio Table

a = Gear <->
b = Transmission Ratio <->
c = Inertia Moment In <kg*m^2>
d = Inertia Moment Out <kg*m^2>
e = Number of Teeth Input <->
f = Number of Teeth Output <->

a	b	c	d	e	f
0	1.0	0.0015	0.005	10	10
1	3.5	0.0015	0.005	10	35
2	2.5	0.0015	0.005	10	25
3	1.5	0.0015	0.005	10	15
4	1.0	0.0015	0.005	10	10
5	0.8	0.0015	0.005	15	12

Fig. 4.46 Gearbox input data specifications window

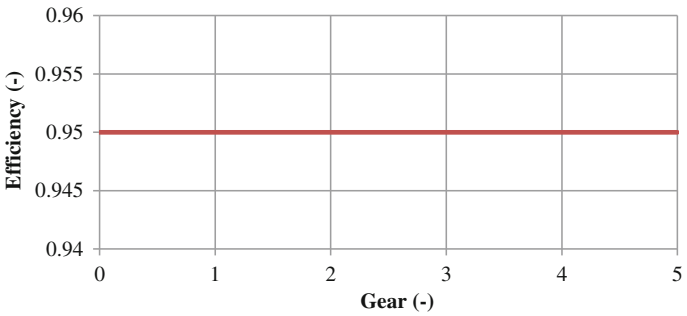


Fig. 4.47 Efficiency and torque loss correction

The dynamic rolling radius can be defined as function of the velocity (Fig. 4.50 and Table 4.41). This characteristic is active when dynamic rolling radius is set from characteristic (a—velocity (km/h), b—rolling resistance factors (%)).

The slip at maximum traction (Fig. 4.51) is, together with the specific traction at infinite slip (Fig. 4.52), the characteristic values for the slip correction factor. The slip correction factor depends on the friction coefficient of the road [1].

The **Brake** component is described by brake data and dimensions (Fig. 4.53). It is possible to define drum brakes as well as disk brakes.

Input data for the two front brakes is the same and also the data for the two rear brakes is the same (Rear Drum Brake Right (10), Front Disk Brake Right (11), Rear Drum Brake Left (12) and Front Disk Brake Left (13)). Double click on the brake icon and enter the following data (Table 4.42).

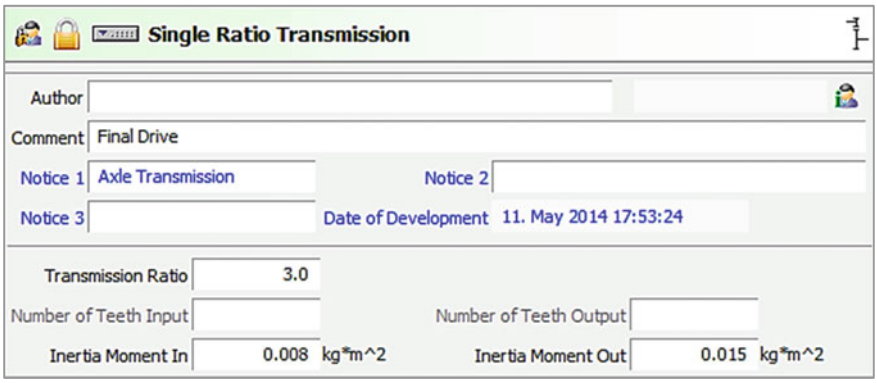


Fig. 4.48 Final Drive input data specifications window

Table 4.39 Final Drive data

Name	Value	Unit
Transmission Ratio	3.000	–
Inertia Moment In	0.010	kg m^2
Inertia Moment Out	0.015	kg m^2
Efficiency	0.950	–

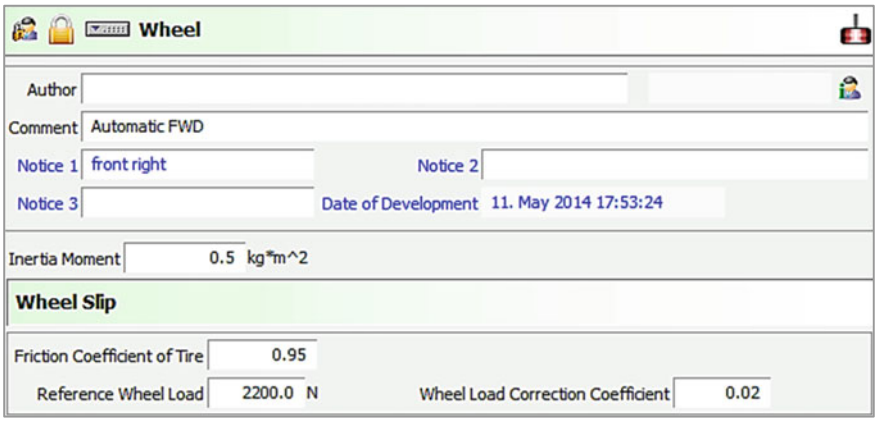


Fig. 4.49 Wheels input data specifications window

Differential (14) unit compensates for discrepancies in the respective rotation rates of the drive wheels. To define component input data double click on the differential icon and enter the following data (Table 4.43, Fig. 4.54).

Table 4.40 Wheels input data

Name	Value	Unit
Wheel Inertia Moment	0.500	kg m^2
Friction Coefficient of Tire	0.950	–
Reference Wheel Load	2200.0	N
Wheel Load Correction Coefficient	0.020	–
Static Rolling Radius	300.0	mm
Circumference	1884.96	mm
Dynamic Rolling Radius	310.0	mm
Circumference	1947.79	mm

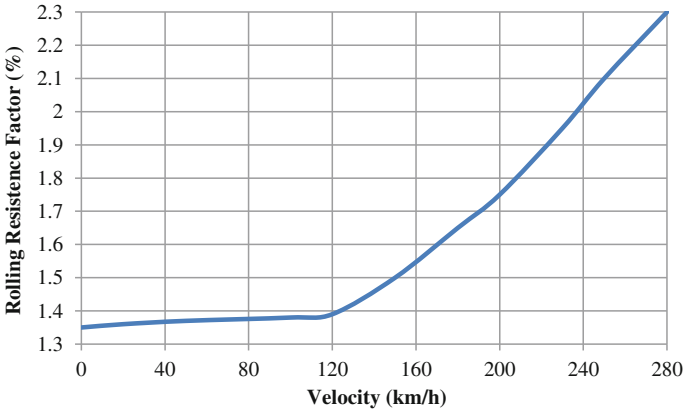


Fig. 4.50 Rolling resistance factor

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component (Fig. 4.55).

The **Cockpit** (15) links the driver and the vehicle (Fig. 4.56). In this component connections are only made via the Data Bus. The pedal positions are transferred to corresponding indicators via the pedal characteristics (Table 4.44) [2].

To define the input data click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)) and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data (Fig. 4.57).

The **Gearbox Control** (16) is required to define an automatic gearbox (Fig. 4.58). In the gearbox control, the gear shifting process can be defined automatically without any influence of the driver.

The gearbox control shifts the gears dependent on a speed or velocity. In the calculation tasks it is decided which of the two shifting strategies is used. The speed or velocity can be defined via the Data Bus. It is possible to define the engine speed and the wheel speed as Ref. [2].

Table 4.41 Rolling resistance factor data

Velocity (km/h)	Rolling Resistance Factor (%)	Velocity (km/h)	Rolling Resistance Factor (%)
0	1.35	180	1.65
20	1.36	200	1.75
50	1.37	230	1.95
100	1.38	250	2.10
120	1.39	280	2.30
150	1.50	180	1.65

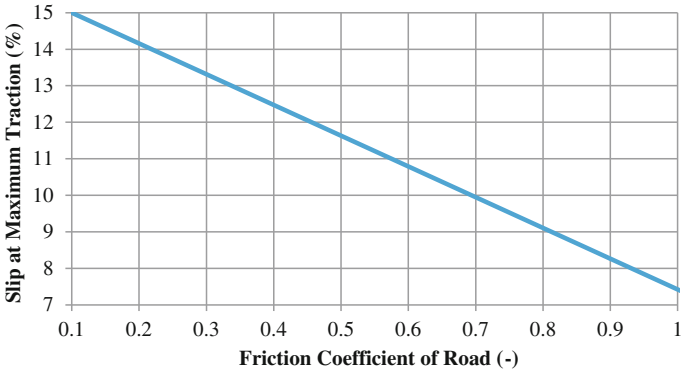


Fig. 4.51 Maximum in the slip characteristic

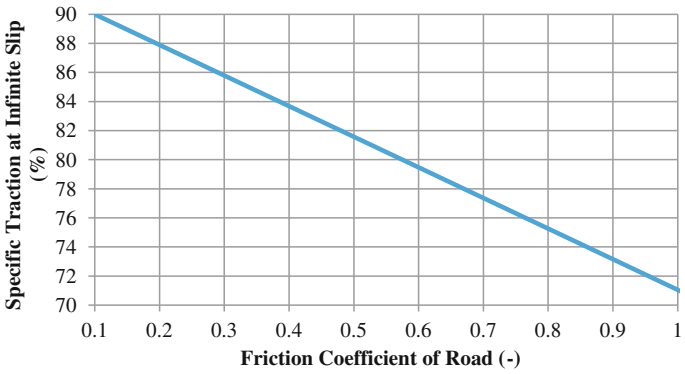


Fig. 4.52 Asymptote of slip characteristic

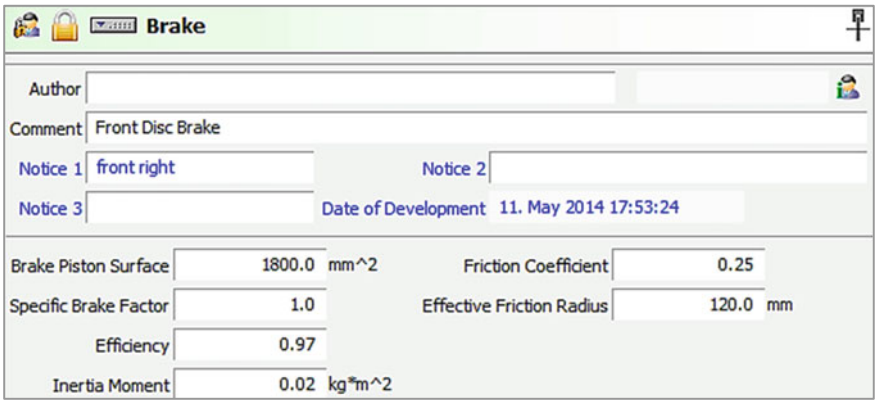


Fig. 4.53 Brake input data specifications window

Table 4.42 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	1800.0	1500.0	1800.0	1500.0	mm^2
Specific Factor	1.00	1.00	1.00	1.00	–
Efficiency	0.97	0.97	0.97	0.97	–
Inertia Moment	0.02	0.02	0.02	0.02	$kg\ m^2$
Friction Coefficient	0.25	0.25	0.25	0.25	–
Friction Radius	120.0	100.0	120.0	100.0	mm

Therefore, it is necessary to define the upshifting and downshifting velocities always only for one gear less than are available in the gearbox.

To define component input data double click on the gearbox control icon and enter the following data (Table 4.45) [3].

The gearbox control is also the connection between the gearbox program and the gearbox.

The velocities for upshifting and downshifting can be checked in the following way: the upshifting velocity of the 2nd gear means that at this velocity the gearbox control is upshifting from the 2nd into the 3rd gear. The downshifting velocity for the 2nd gear means that at this velocity the gearbox control is downshifting from the 3rd into the 2nd gear.

The **Gearbox Program** (17) is used for automatic gearboxes in combination with the gearbox control (Fig. 4.59). The gearbox program allows for a more complicated gear shifting process than the gearbox control, as the load signal of the engine is considered. The gearbox program shifts the gears according to given

Table 4.43 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.00	–
Inertia Moment In	0.02	kg m^2
Inertia Moment Out1	0.02	kg m^2
Inertia Moment Out2	0.02	kg m^2

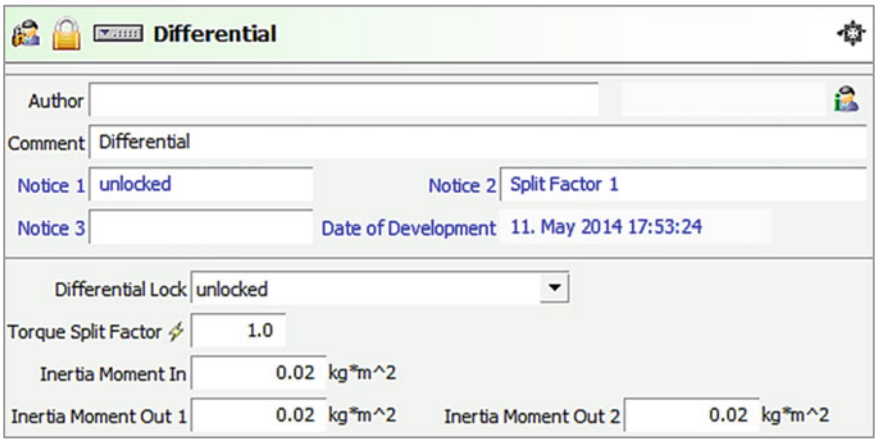


Fig. 4.54 Differential input data specifications window

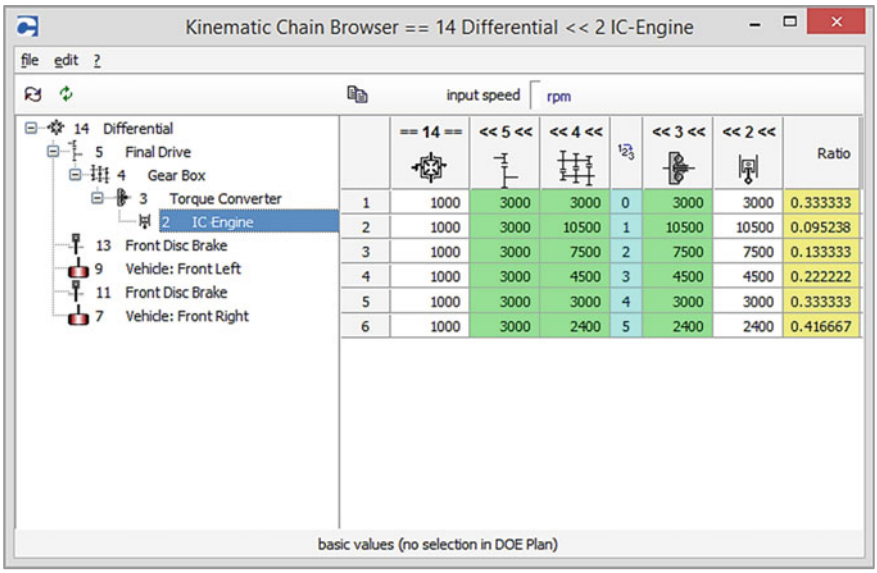


Fig. 4.55 Kinematic Chain Browser

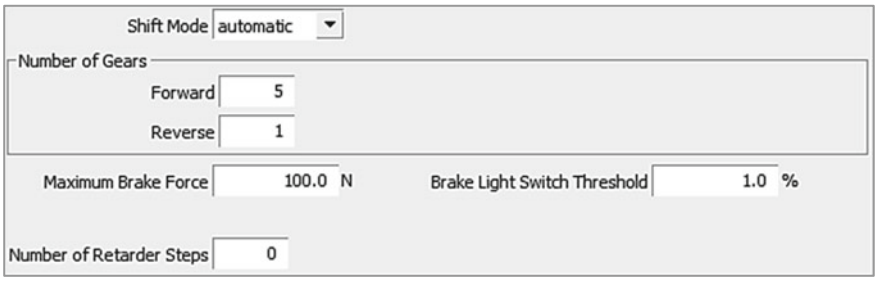


Fig. 4.56 Cockpit input data specifications window

Table 4.44 Cockpit input data

Name	Value	Unit
Shift Mode	Automatic	–
Number of Gears Forward	5.00	–
Number of Gears Back	1.00	–
Maximum Brake Force	100.0	N
Brake Light Switch Threshold	1.00	%
Number of Retarder Steps	0.00	–

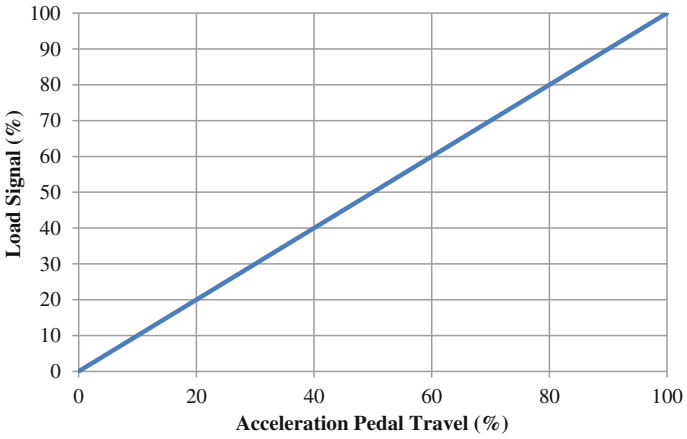


Fig. 4.57 Pedal characteristic

curves. The curves are given as a function of the load signal and the engine speed. The target gear determined by the program is transmitted to the gearbox control that transmits it to the gearbox.

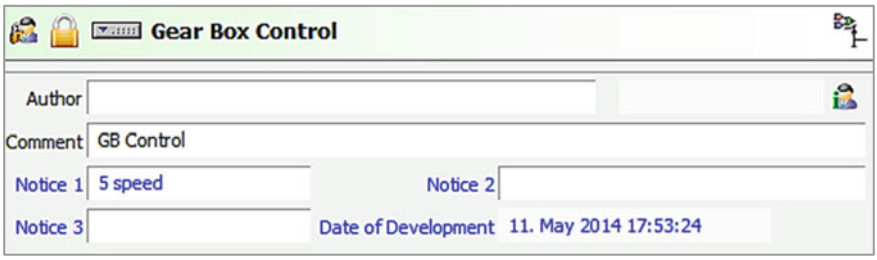


Fig. 4.58 Gearbox control input data specifications window

Table 4.45 Gearbox control input data

Shifting According to Velocity		
a—Gear (–)	b—Upshifting (km/h)	c—Downshifting (km/h)
1	25	20
2	50	40
3	75	60
4	100	80
Shifting According to Speed		
a—Gear (–)	b—Upshifting (1/min)	c—Downshifting (1/min)
1	3000	1500
2	3000	1500
3	3000	1500
4	3000	1500
Shifting According to Speed in next Gear		
a—Gear (–)	b—Upshifting (1/min)	c—Downshifting (1/min)
1	2000	2500
2	2000	2500
3	2000	2500
4	2000	2500

Furthermore, the curves could be optimized using iSIGHT interface module. These optimized curves (optimized shifting program) could also be used as input curves for the gearbox program [2].

The gear shifting process is done similar to the gearbox control. The only difference is the dependence on the load signal of the engine. If the shifting program should be defined not by speed but by velocity, the Data Bus input velocity must be connected.

The units of the shifting program and the optimized shifting program influence each other. This means that if one of these programs is loaded with a different unit, the other program also gets this new unit.

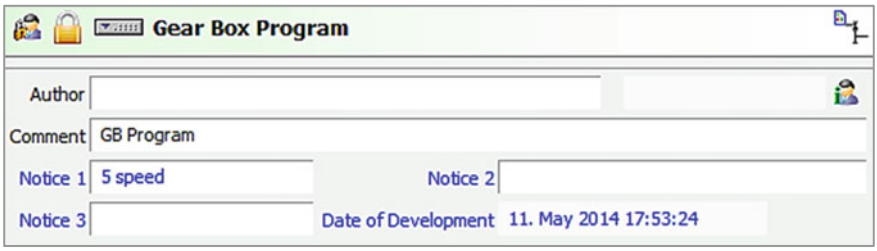


Fig. 4.59 Gearbox program input data specifications window

With the properties switches shifting program 2–5 up to four additional shifting programs can be defined (a—gear (–), b—load signal (%), c—speed upshifting (1/min) and d—speed downshifting (1/min)).

With the Data Bus input shifting program selector (which provides a double value), interpolations between the defined shifting programs can be done (Fig. 4.60a, b and Tables 4.46, 4.47) [3].

The speeds for upshifting and downshifting can be checked in the following way: the upshifting speed of the 2nd gear with the special load signal means that at this speed with this load signal the gearbox control is upshifting from the 2nd into the 3rd gear. The downshifting speed for the 2nd gear with the special load signal means that at this speed with this load signal the gearbox control is downshifting from the 3rd into the 2nd gear.

The **ASC Anti-Slip Control** (18) checks the force transmission factor of all connected wheels (Fig. 4.61).

The ASC is only active when a model is calculated quasi-stationary in combination with special drivetrain configurations and does not require data entry.

If the ASC is used for calculations in simulation mode this switch can be activated. In this case the parameters for the PID controller can be set proportional (–), differential (s), and integral parameter (1/s).

Catalyst (19) or exhaust systems consider the effects of the catalytic converter and soot filler on the raw emissions of the engine (Fig. 4.62).

To define component input data double click on the catalyst icon and enter the following data (Table 4.48).

Conversion efficiencies of the different emissions (NO_x, CO, HC, and Soot) can be defined dependent on the actual temperature of the catalytic converter.

Conversion efficiencies curve can be defined as function of a—temperature (°C) and efficiency (–) (Fig. 4.63 and Table 4.49—NO_x conversion efficiencies, Fig. 4.64 and Table 4.50—CO conversion efficiencies, Fig. 4.65 and Table 4.51—HC conversion efficiencies).

The heat transfer Gas/Cat (Table 4.52 and Fig. 4.66) are the proportion of the exhaust gas which is transferred to the exhaust system and can be defined as a function of a—temperature (°C) and b—heat-up proportion of exhaust gas energy (%) [1].

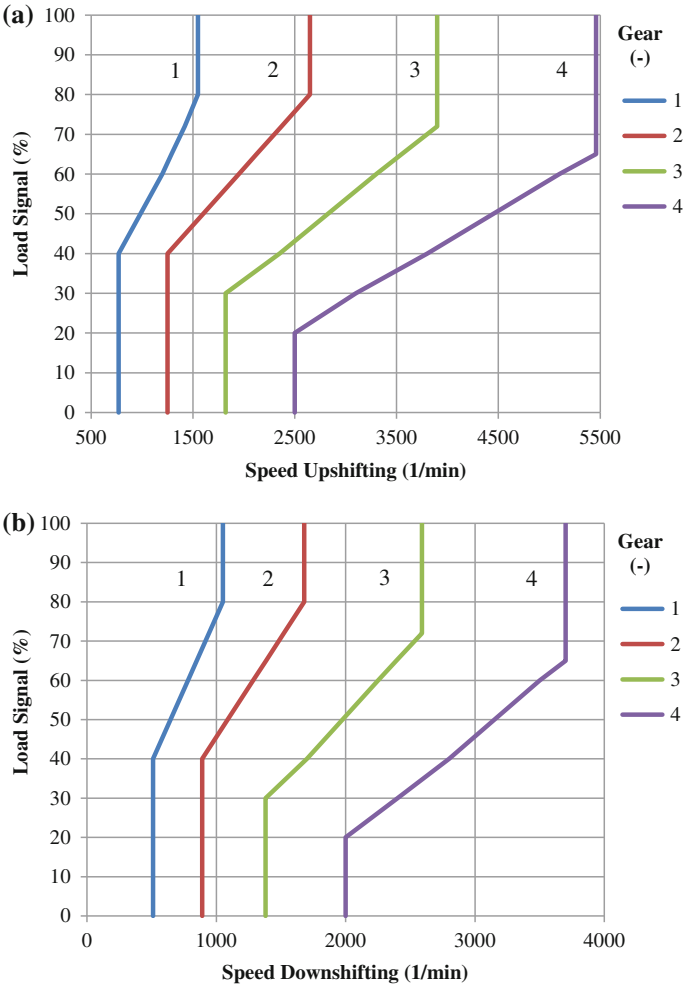


Fig. 4.60 Shifting programs standard. **a** speed upshifting. **b** speed downshifting

Table 4.46 Upshifting program data

(a)										
1	(b)	0	20	30	40	60	65	72	80	100
	(c)	770	770	770	770	1200	1290	1420	1550	1550
2	(b)	0	20	30	40	60	65	72	80	100
	(c)	1250	1250	1250	1250	1950	2125	2370	2650	2650
3	(b)	0	20	30	40	60	65	72	80	100
	(c)	1820	1820	1820	2350	3300	3550	3900	3900	3900
4	(b)	0	20	30	40	60	65	72	80	100
	(c)	2500	2500	3100	3800	5100	5460	5460	5460	5460

Table 4.47 Downshifting program data

(a)										
1	(b)	0	20	30	40	60	65	72	80	100
	(c)	510	510	510	510	780	848	942	1050	1050
2	(b)	0	20	30	40	60	65	72	80	100
	(c)	890	890	890	890	1285	1384	1522	1680	1680
3	(b)	0	20	30	40	60	65	72	80	100
	(c)	1380	1380	1380	1700	2250	2392	2590	2590	2590
4	(b)	0	20	30	40	60	65	72	80	100
	(c)	2000	2000	2400	2800	3500	3700	3700	3700	3700



Fig. 4.61 ASC input data specifications window

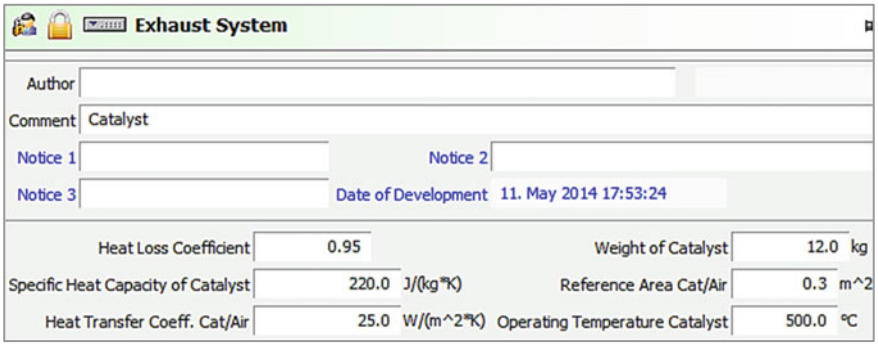


Fig. 4.62 Catalyst input data specifications window

The **Monitor** component (20) can be introduced, if the calculation run must be detected. It is possible to show some results of the calculation while the calculation is running.

Table 4.48 Catalyst input data

Name	Value	Unit
Heat Loss Coefficient	0.950	–
Weight of Catalyst	12.00	kg
Specific Heat Capacity of Catalyst	220.0	J/kg K
Reference Area Cat/Air	0.300	m^2
Heat Transfer Coefficient Cat/Air	25.00	W/m^2 K
Operating Temperature Catalyst	500.0	°C

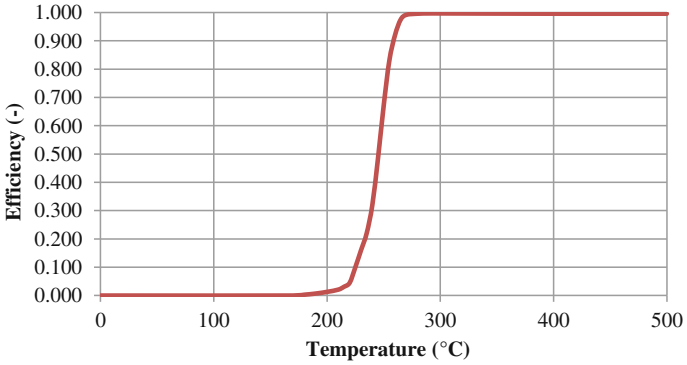


Fig. 4.63 NO_x conversion efficiencies

Table 4.49 NO_x conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

Click on the description of Data Bus tab and open the following dialog. To select a Data Bus channel, click to access at the available list. Enter the text for the description and then click on to select the unit (Fig. 4.67).

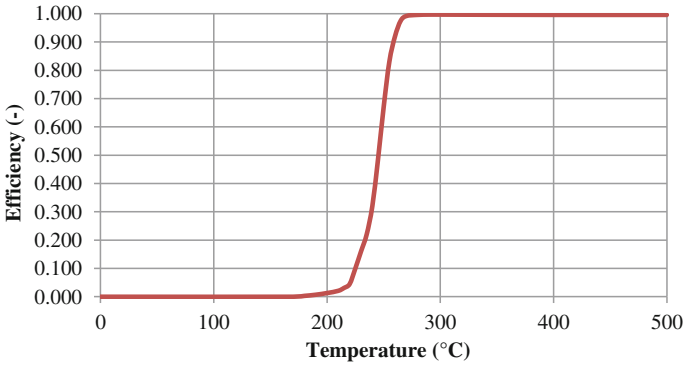


Fig. 4.64 CO conversion efficiencies

Table 4.50 CO conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

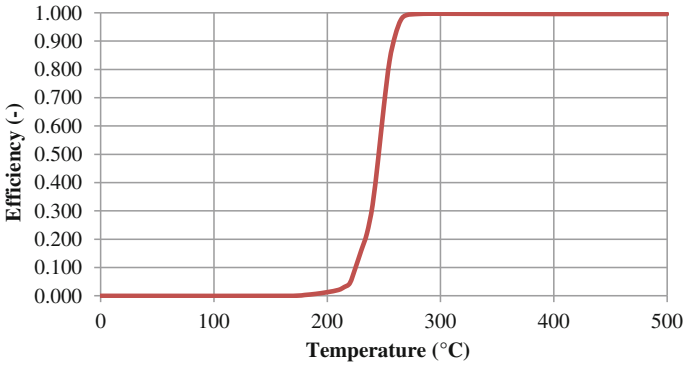


Fig. 4.65 HC conversion efficiencies

Table 4.51 HC conversion efficiencies data

Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)	Temperature (°C)	Efficiency (–)
0	0.000	225	0.100	265	0.975
170	0.000	230	0.160	270	0.992
180	0.003	235	0.220	280	0.996
190	0.007	240	0.320	290	0.997
200	0.013	245	0.485	300	0.997
210	0.021	250	0.670	400	0.996
215	0.031	255	0.830	500	0.996
220	0.045	260	0.920	–	–

Table 4.52 Heat transfer Gas/Cat data

Temperature (°C)	Heat-Up Proportion of Exhaust Gas Energy (%)
−30	41
210	39
270	65
500	64
600	64
1000	64

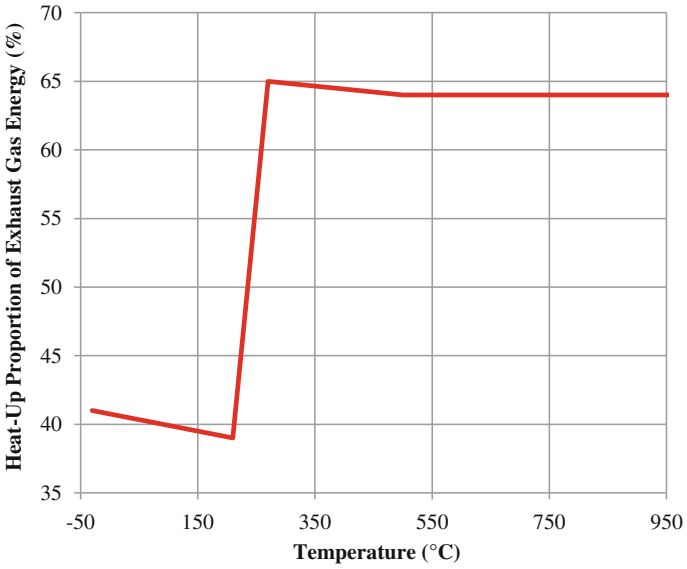


Fig. 4.66 Heat transfer Gas/Cat

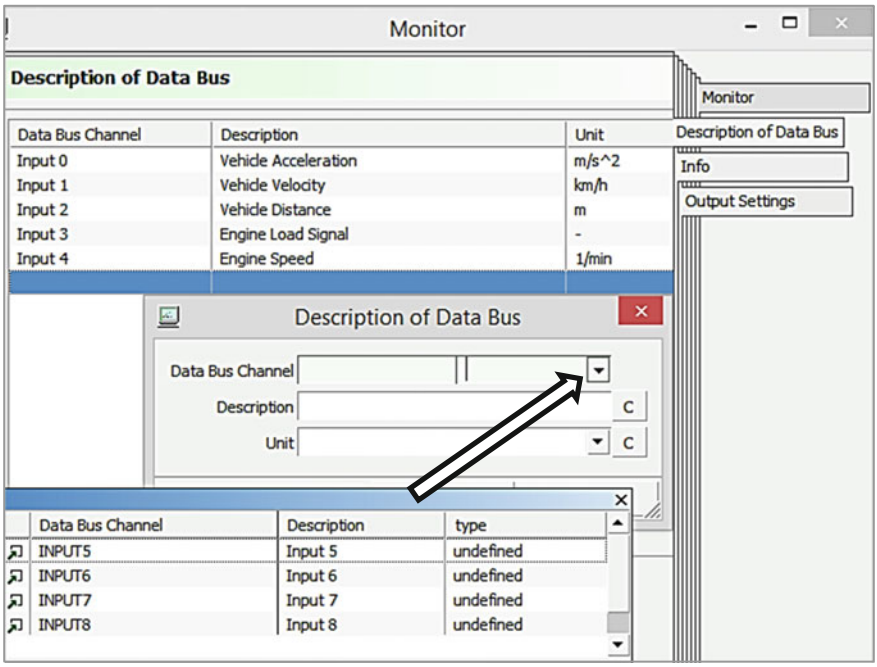


Fig. 4.67 Monitor description of Data Bus

4.2 Run Simulation

4.2.1 Result Manager

To run a simulation for each model, there are five different options for calculation [2]:

- Single Calculation is a regular calculation with the input data supplied in the components. The output of the result defines which components result will be written and available in the Result Manager.
- Matrix Calculation is used for multiple calculations and to evaluate the effect of varying the values of input parameters on vehicle performance, consumption and emissions. The results can be viewed for each varied calculation.
- Component Variation is used for multiple calculations and the calculation consists of sub-calculations in which components are replaced by components of the same type. The results can be viewed in the Result Manager.
- System Variation is used for multiple calculations from a list of all the model systems. The results can be viewed similar to Component Variation.
- Batch Calculation is used for calculations series of different projects, either Single Calculation, Matrix Calculation with DoE option and Component Variation with DoE option.

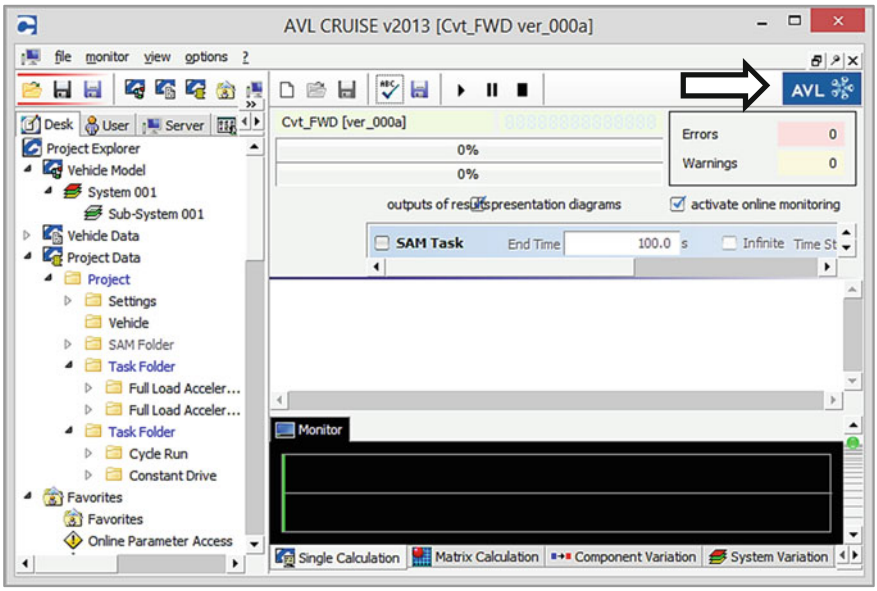


Fig. 4.68 Start calculation

To run the calculation in the Desk Area click on Calculation Center or click on AVL blue button in the upper right corner (Fig. 4.68). Click on to "Start Calculation" button to run the simulation.

After the completion of the simulation click on the Result Manager in the Navigation Frame (Fig. 4.69) and expand the task of which the results should be viewed. The selected objects are shown in the right section of the window.

Project information can be viewed in the main window by selecting info in the tree structure or by double clicking info in the right window. The window shows general information: project name, author, vehicle model, drivetrain model, date, and state (regarding errors), then the tree structure of the folder with defined Calculation Tasks (different status for run or not run is shown using blue/gray color). The picture of the Vehicle Model is also displayed.

One output file is produced for each component in the Vehicle Model and each Calculation Task. Data for diagrams are extracted from these files and are shown as Energy Flow Graphics, presentation diagrams for current tasks and standard diagrams for used components.

In the tree structure of the Result Manager all defined Calculation Task folders are shown separately for each task. The folders with results are shown in color; tasks which are not simulated are gray. Files for each Calculation Task are located inside the respective folder. In Result Manager, all components are listed where results have been written in pages mode or data sources mode (Fig. 4.70).

The result output for components is selected with output in the properties window of the respective component [4].

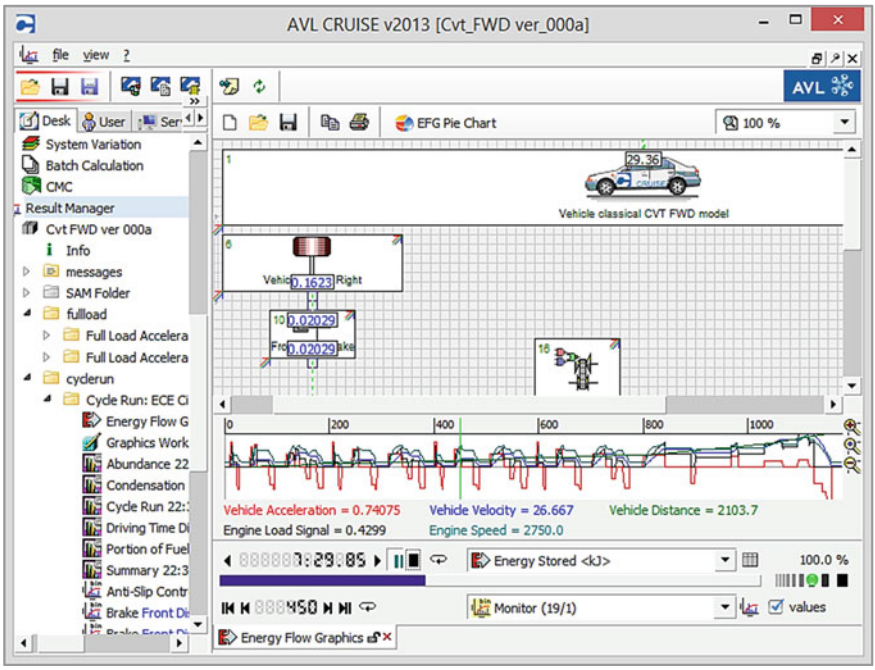


Fig. 4.69 Result Manager window

Select as defined in module for output of results in the folder of the corresponding calculation task. There are two types of result outputs available with the Result Manager: standard diagrams and presentation diagrams.

Standard diagrams (Fig. 4.71) are created separately for each component and only contain results of the individual component and represent time histories of the single components.

Standard diagrams have a predefined representation page, which can only be changed in some parts. Standard diagrams are opened by selecting the respective calculation task in the tree structure of Result Manager and then selecting the corresponding component.

The pages mode sidebar is divided into a list of predefined standard diagram pages for the respective component and TeimView Assistant with a tree structure of components with all available curves and the current parameter for current diagram of respective component with the list of all used curves. TeimView has two tabs: pages and data sources. Pages are used to view results as curves in standard diagram and data sources in tables as numerical data for the respective component for analyzing and extracting [2].

The data sources mode sidebar (Fig. 4.72) has a tree structure where the data source, data file, and table are shown. In data sources view there is a list of all curve data that can be shown.

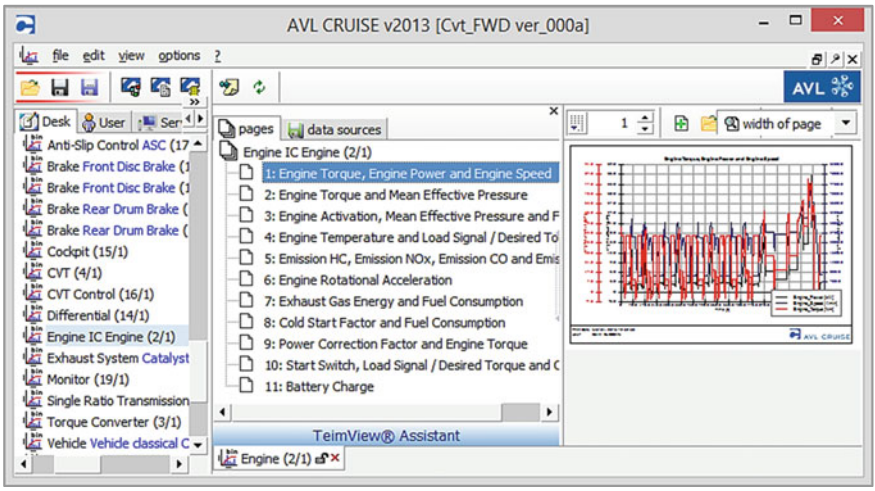


Fig. 4.70 Result Manager pages mode

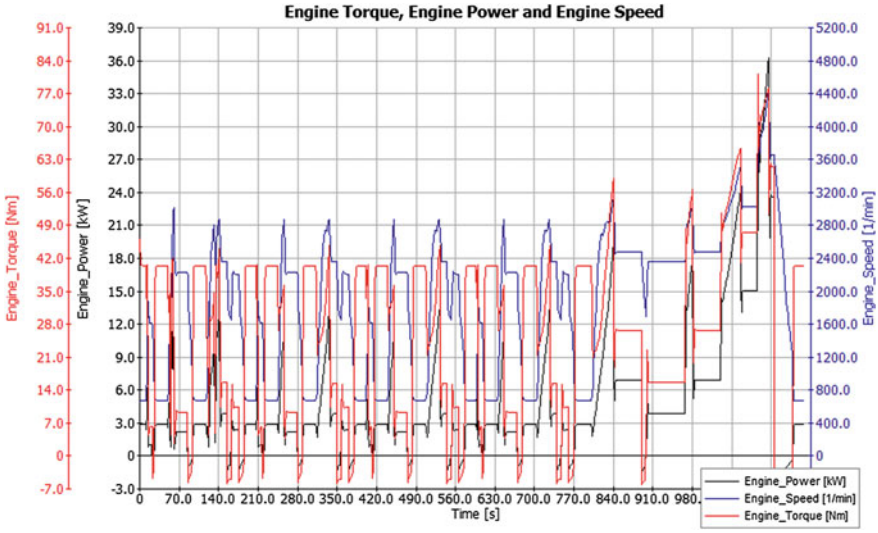


Fig. 4.71 Standard diagrams

The Energy Flow Graphics feature can be selected in the Result Manager (Fig. 4.73). An animation shows the flow between the drivetrain components over time of the following parameters: Current (A), Energy Stored (kJ), Energy (kJ), Power (kW), Speed (1/min), Velocity (km/h), Torque (Nm), Force (N), Voltage (V).

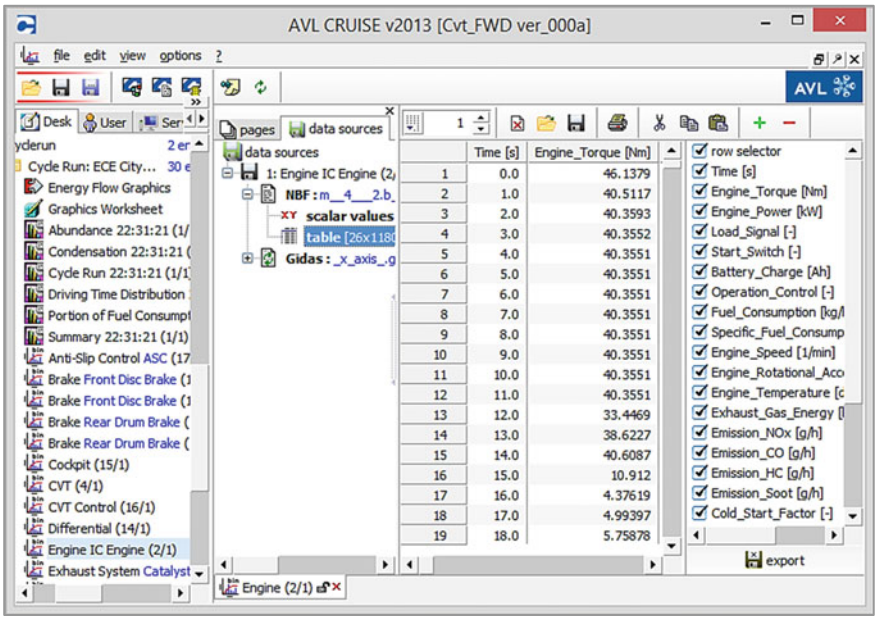


Fig. 4.72 Result Manager data sources mode

The animation can be controlled by using the play, pause, stepwise, stop, repeat, velocity switches. A time-bar, showing the actual simulation time, can be moved to a certain time-step with the mouse.

Below the flow graphics a monitor is shown which displays the result curves of the selected components. With the zoom-option, the horizontal can be scaled so that long cycles can also be viewed properly.

In addition to the graphical representation, the associated values can also be viewed in the monitor as well as in the drivetrain flow graphics.

The values of the Energy Flow Graphics can also be displayed in a pie chart. Clicking the button EFG pie chart opens an area where the segments can be added or removed with the buttons "+" and "−".

The association between a segment and a component parameter can be done by adding the segment in the segment list and then a left mouse-click on a connector of the component (Fig. 4.74). Several connectors can be chosen for one segment. In that case, the segment represents the sum of all associated values. The segment list consists of the absolute segment values as well as of the values in terms of percentages [2].

The task of the mode trimap is to construct a 3D surface and describe it by isolines. The input data (3D points) are projected into the x-y-surface and are triangulated (in 2D). The isolines are created by an intersection list (Fig. 4.75) [2].

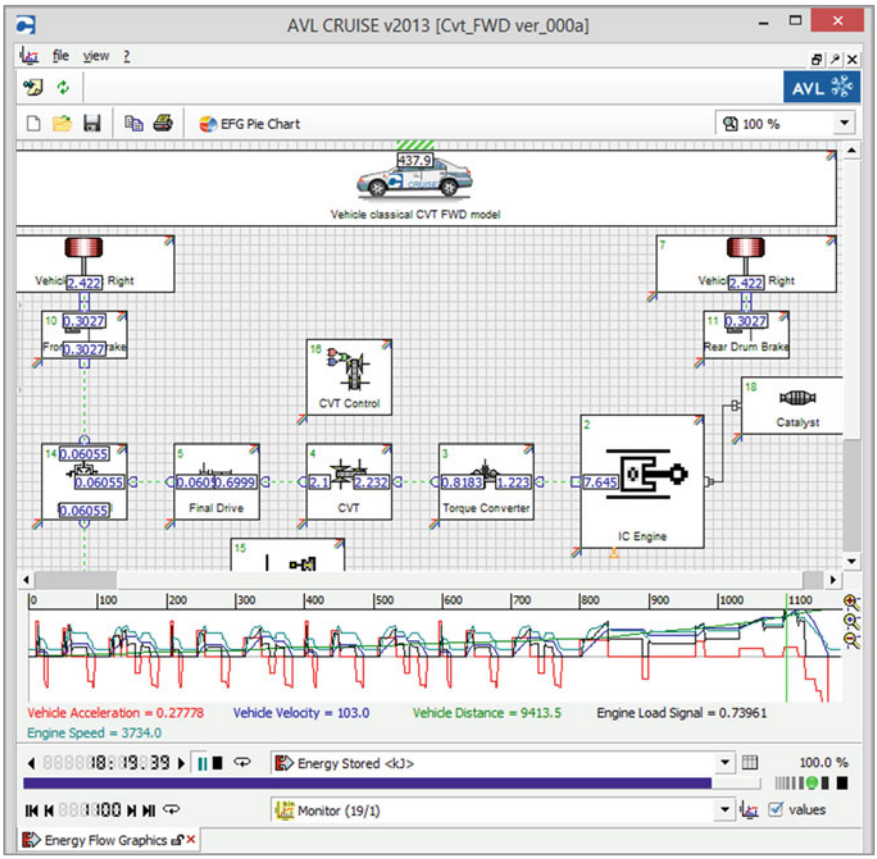


Fig. 4.73 Energy Flow Graphics

4.2.2 Standard Diagrams

To evaluate the fuel economy characteristics of the IC Engine motored bus a typical NEDC cycle was simulated (Fig. 4.76).

The total distance of this cycle is 1.0931 m, the total time is 1180 s, idle standing time is 267 s, average speed including stops is 33.35 km/h, average driving speed excluding stops is 43.10 km/h, average acceleration is 0.506 m/s^2 and maximum acceleration is 1.042 m/s^2.

The statistical percentages of IC Engine operating region are found in condensation map and it is show in Fig. 4.77.

Driving time distribution in consumption map is show in Fig. 4.78, the engine speed for IC Engine is show in Fig. 4.79, the engine torque for IC Engine is show in Fig. 4.80, engine power for IC Engine is show in Fig. 4.81 and the mean effective pressure for IC Engine is show in Fig. 4.82.

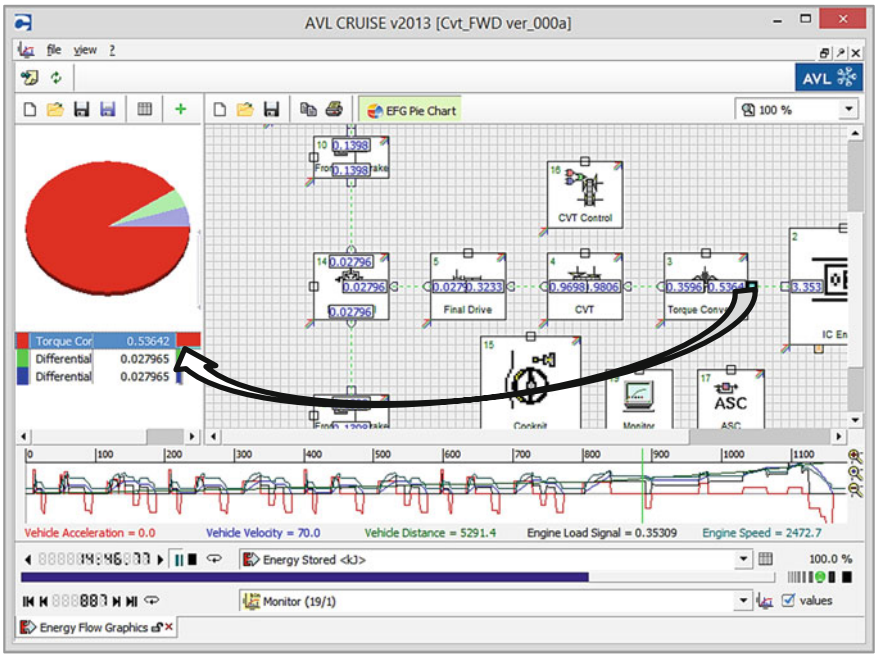


Fig. 4.74 EFG pie chart

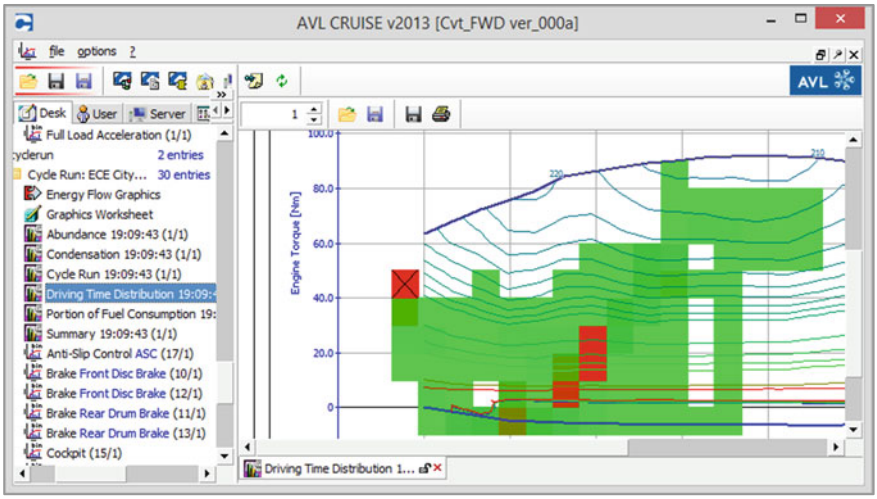


Fig. 4.75 Trimap diagram

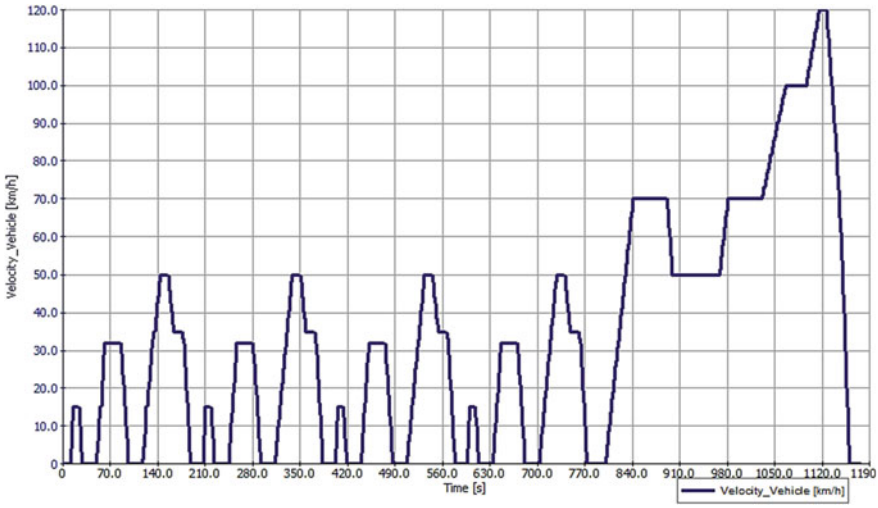


Fig. 4.76 Typical NEDC cycle

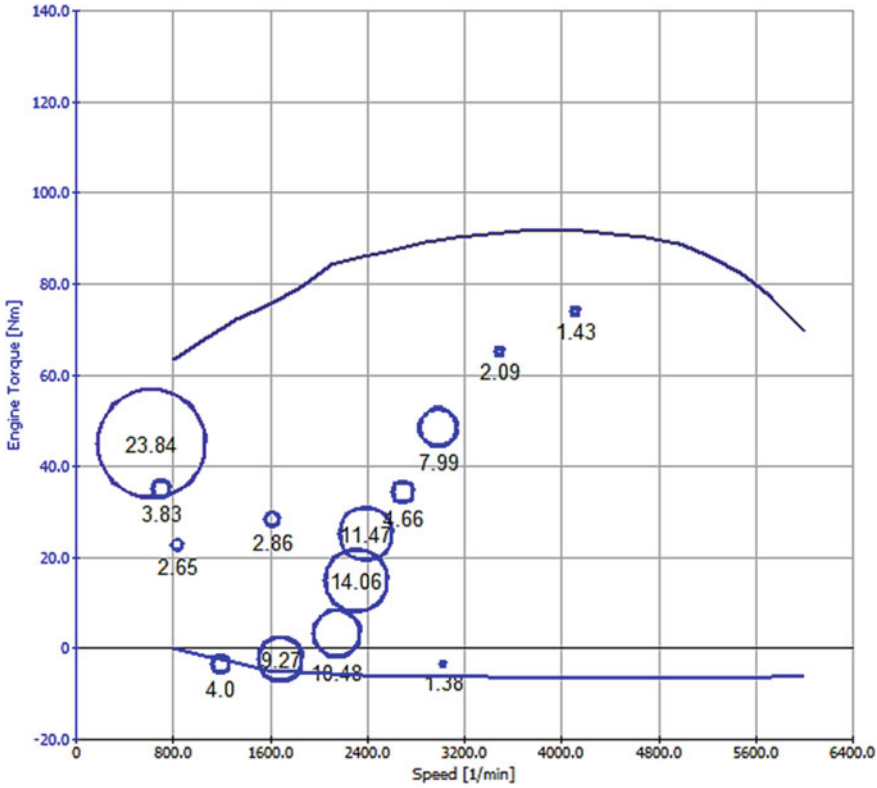


Fig. 4.77 Statistical percentages of engine operating region

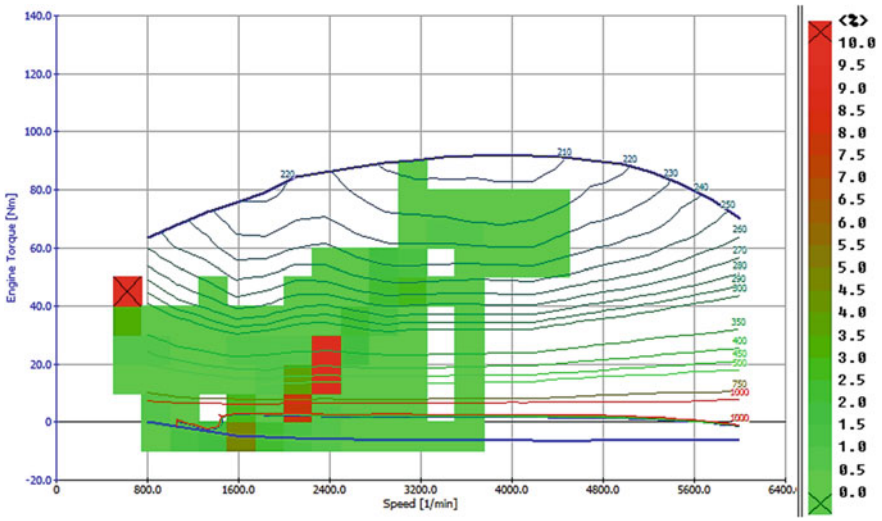


Fig. 4.78 Driving time distribution in consumption map

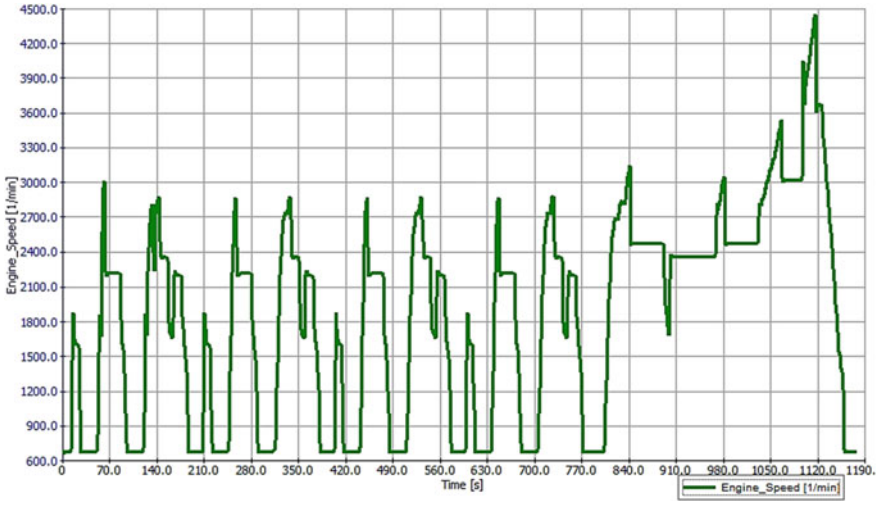


Fig. 4.79 Engine speed for IC Engine

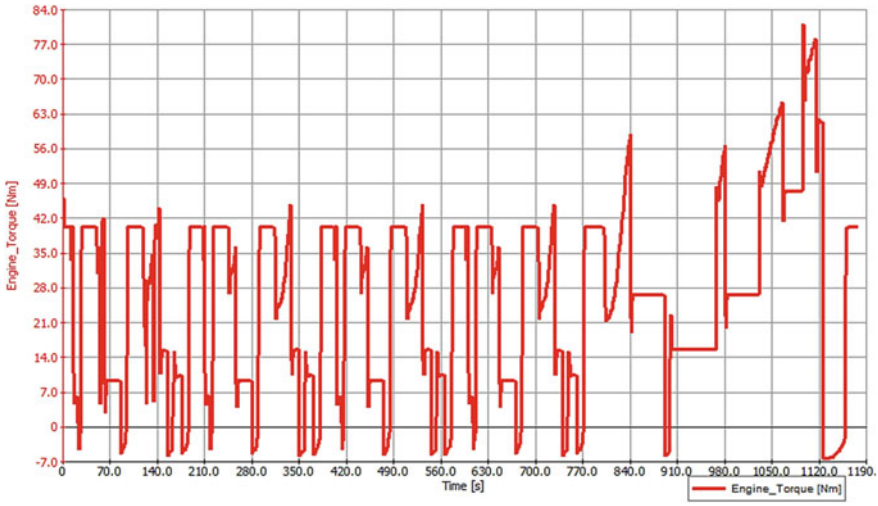


Fig. 4.80 Engine torque for IC Engine

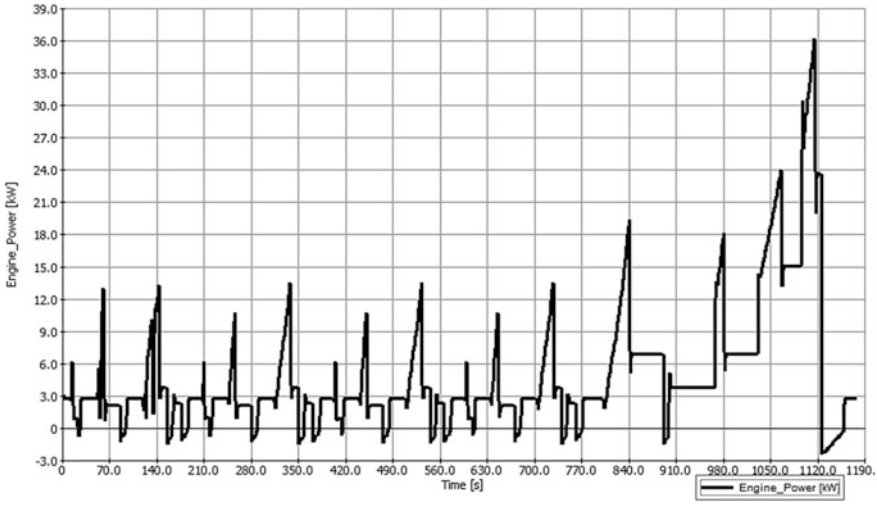


Fig. 4.81 Engine power for IC Engine

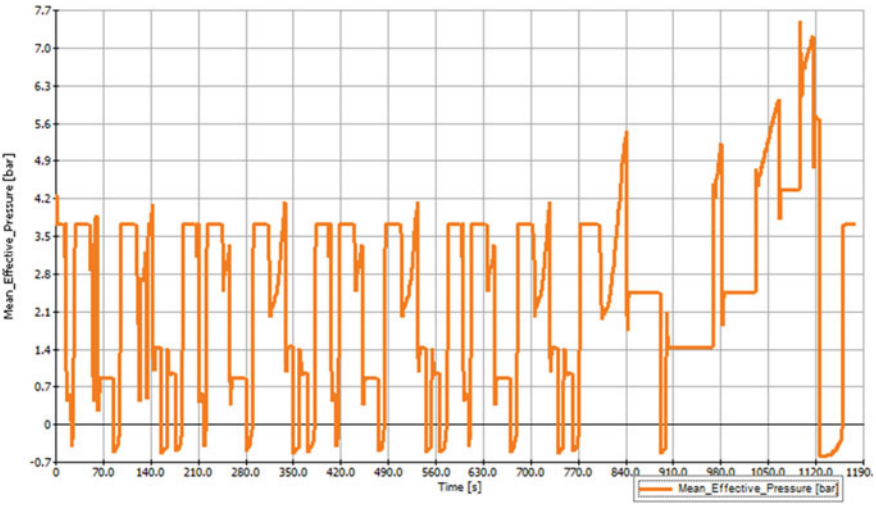


Fig. 4.82 Mean effective pressure for IC Engine

References

1. AVL Cruise (2011) Primer. AVL List GmbH, Graz, Austria, Document no. 04.0103.2011, Edition 06.2011
2. AVL Cruise (2011) Users Guide. AVL List GmbH, Graz, Austria, Document no. 04.0104.2011, Edition 06.2011
3. AVL Cruise (2011) Gear Shifting Program (GSP). AVL List GmbH, Graz, Austria, Document no. 04.0114.2011, Edition 06.2011
4. AVL Cruise (2011) Notes. AVL List GmbH, Graz, Austria, Document no. 04.0102.2011, Edition 06.2011

Chapter 5
Hybrid Powertrain Configuration Model and Simulation

5.1 Hybrid Vehicle Model Creation

5.1.1 Hybrid CVT Model

This chapter describes how to create and run the model of a hybrid CVT front-wheel drive. To place a component in the working area, click on the component group with the left mouse button, move the mouse over the required component, and then click and drag the component into the vehicle model area. Arrange the components as shown in the following figure (Fig. 5.1) and connect the components as specified in the diagram. All the connections in the Data Bus for this model are described in Table 5.1 [1].

Place the following components in the working area: Vehicle (1), IC Engine (2), Clutch (3), CVT Continuously Variable Transmission (4), Final Drive (5), Vehicle Front Right (6), Vehicle Front Left (7), Vehicle Rear Right (8), Vehicle Rear Left (9), Rear Drum Brake (10), Front Disk Brake (11), Front Disk Brake (12), Rear Drum Brake (13), E-Machine (14), Differential (15), Cockpit (16), CVT control (17), Battery H (18), MATLAB® DLL (19), Delta Torque CE (20), Delta Torque Brake (21), Total Torque (22), and Monitor (23).

The **Vehicle** (1) is one of the main objects in a model. This component contains general data of the vehicle, such as nominal dimensions and weights. Only one vehicle component is required in a model. Road resistances and dynamic wheel loads are calculated for road and dynamometer runs based on the dimensions and the load state. The wheel loads are calculated considering motion. The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated [2].

To define component input data (Table 5.2) double click on the icon or click on it with the right mouse button and select edit to open the following window (Fig. 5.2).

The properties window is accessed through properties button in the input data window, or from the pop-up menu by selecting "properties." Selected parameters

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_5

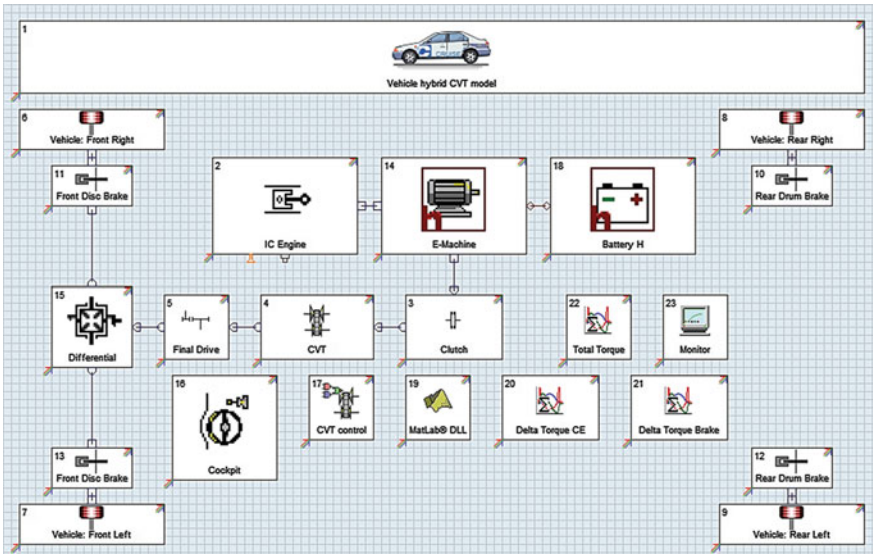


Fig. 5.1 Complete CVT hybrid model

have influence on needed component data input for calculation (Fig. 5.3). With these settings, it is also possible to run a calculation with minimal input data, as the input fields of the unavailable data can be switched off.

IC Engine (2) component contains a model for an internal combustion engine. The characteristic curves for the full load, the fuel consumption, and others can be freely defined by the user [2]. It is possible to define a gasoline engine as well as a diesel engine. In this component a temperature model is included to consider the influence of the temperature on the fuel consumption and emissions while the engine is cold. The engine will be modelled by a structure of characteristic maps.

To define component input data (Table 5.3) double click on the icon or click on it the right mouse button and select edit to open the following window (Fig. 5.4).

The properties window is accessed through properties button in input data window, or from pop-up menu (Fig. 5.5).

To load IC Engine characteristic click on the Full Load Characteristic tab (Fig. 5.6). Add rows by clicking on and enter the following data (Table 5.4) [1].

The Motoring Curve (Fig. 5.7) will be defined similar to the Full Load Characteristic either as power dependent on the engine speeds (Table 5.5).

At the Fuel Consumption Map (Table 5.6 and Fig. 5.8) the actual fuel consumption for stationary operation is listed depending on the brake mean pressure with the engine speed (a—speed (1/min), b—BMEP (bar), c—volume flow (l/h)).

In the emission maps the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—mass flow (kg/h), namely NO_x emission map in

Table 5.1 Data Bus connections

Component Requires	Input Information	Component Delivering	Output Information
Battery H	Ambient Temperature	Cockpit	Course Ambient
Brake Rear Drum	**Brake Pressure**	Delta Torque Brake	Brake Pressure
Brake Front Disk	**Brake Pressure**	Delta Torque Brake	Brake Pressure
Brake Rear Drum	**Brake Pressure**	Delta Torque Brake	Brake Pressure
Brake Front Disk	**Brake Pressure**	Delta Torque Brake	Brake Pressure
Clutch	**Desire Clutch Release**	Cockpit	Desire Clutch Release
Cockpit	**Gear Indicator**	CVT	Current Gear
	Operation Control 0	IC Engine	Operation Control
	Speed	IC Engine	IC Engine Speed
CVT	**Desired Transmission**	CVT Control	Desired Transmission
	Temperature	E-Machine	Temperature
CVT Control	**Current Transmission**	CVT	Current Transmission
	Load Signal	Delta Torque CE	Load Signal
	Speed	IC Engine	IC Engine Speed
	Torque	Total Torque	Torque
	Velocity	Cockpit	Velocity
E-Machine	Ambient Temperature	Cockpit	Course Ambient
	Load Signal	MATLAB® DLL	Load Signal
IC Engine	**Load Signal**	Delta Torque CE	Load Signal
	Start Switch	MATLAB® DLL	Start Switch
Delta Torque CE	**Load Signal Cockpit**	Cockpit	Load Signal
	Load Signal EMS	MATLAB® DLL	Load Signal EMS
Delta Torque B	Brake Pressure	Cockpit	Brake Pressure
	Brake Pressure EMS	MATLAB® DLL	Brake Pressure EMS

(continued)

Table 5.1 (continued)

Component Requires	Input Information	Component Delivering	Output Information
Total Torque	Torque	E-Machine	Torque
	Torque Flywheel	IC Engine	Torque Flywheel
MATLAB® DLL	IC Engine Speed	IC Engine	IC Engine Speed
	Torque Flywheel	IC Engine	Torque Flywheel
	Load Signal	Cockpit	Load Signal
	Brake Pressure	Cockpit	Brake Pressure
	Velocity	Vehicle	Velocity
	Battery Charge	Battery H	Battery Charge
	Start Switch	Cockpit	Start Switch
	Current Ratio	CVT	Current Ratio
	Clutch Release	Clutch	Clutch Release
	Current	Battery H	Current
Monitor	Vehicle Acceleration	Vehicle Hybrid	Acceleration
	Vehicle Velocity	Vehicle Hybrid	Velocity
	Vehicle Distance	Vehicle Hybrid	Distance
	IC Engine Load Signal	IC Engine	Actual Load Signal
	IC Engine Speed	IC Engine	IC Engine Speed
Single Ratio	Temperature	Cockpit	Course Ambient

Table 5.2 Vehicle components input data

Name	Value	Unit
Gas Tank Volume	0.050	m^3
Distance from Hitch to Front Axle	3200.0	mm
Height of Support Point at Bench Test	100.0	mm
Wheel Base	2690.0	mm
Distance of Gravity Center empty/half/full	1080.0/1090.0/1100.0	mm
Height of Gravity Center empty/half/full	560.0/550.0/540.0	mm
Height of Hitch empty/half/full	390.0/380.0/370.0	mm
Tire Inflation Pressure Front Axle	2.200	bar
Tire Inflation Pressure Rear Axle	2.200	bar
Curb Weight	1300.0	kg
Gross Weight	1600.0	kg
Frontal Area	2.000	m^2
Drag Coefficient	0.300	–

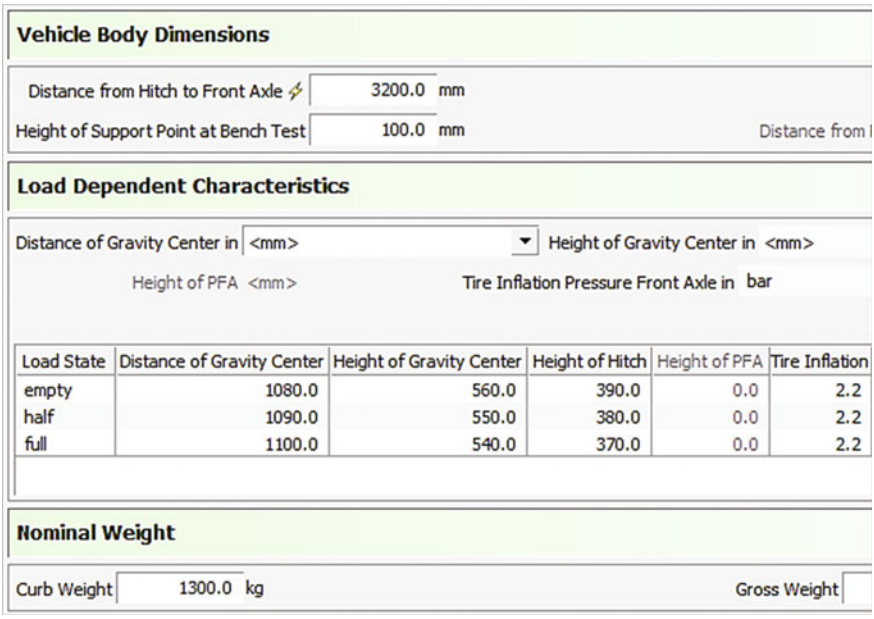


Fig. 5.2 Vehicle input data specifications window

Fig. 5.9 and Table 5.7, CO emission map in Fig. 5.10 and Table 5.8, HC emission map in Fig. 5.11 and Table 5.9) [1].

The **Clutch** (3) makes stationary idle possible, transition to motion, and interruption of the power flow (Fig. 5.12). The clutch slips to compensate for the

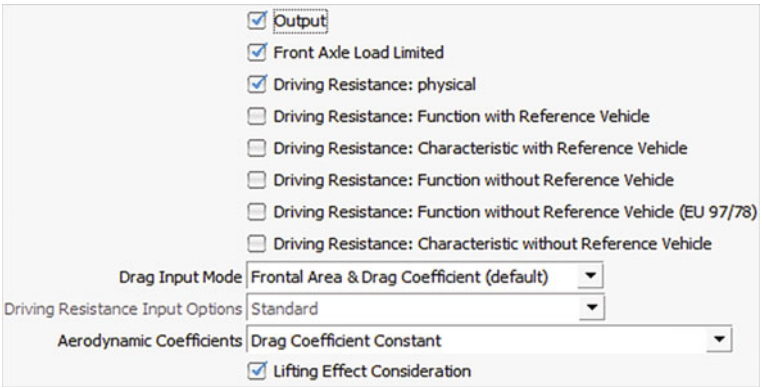


Fig. 5.3 Properties of Vehicle

Table 5.3 IC Engine components input data

Name	Value	Unit
Engine Displacement	1460.0	cm^3
Engine Working Temperature	90.00	°C
Number of Cylinders/Strokes	4/4	–
Idle/Maximum Speed	790.0/5600.0	1/min
Inertia Moment	0.190	kg m^2
Response Time	0.040	s
Heating Value for Gasoline	42700.0	kJ/kg
Fuel Density	0.720	kg/l
Idle Consumption	0.500	l/h
Idle Emission NO_x/CO/HC	0.0015/0.075/0.050	kg/h

difference in the rotational speeds of engine and drive train when the vehicle is set in motion. When a change in operation conditions makes it necessary to change gears, the clutch disengages the engine from the drivetrain for the duration of the procedure [2].

The clutch can be used together with a CVT gearbox and it is only necessary for starting. In this case, the clutch is controlled by the control module CVT control. To define component input data (Table 5.10) double click on the icon and select edit to open the following window (Fig. 5.13).

The pressure force is the axial force when the frictional surfaces are pressed together. This pressure force depends on the clutch release. With the pressure force the transmitted torque can be calculated by considering the dimensions (a—clutch release (%), b—pressure force (N)).

CVT (4) can convert every point on the engine operating curve to an operating curve of its own, and every engine operating curve into an operating range within

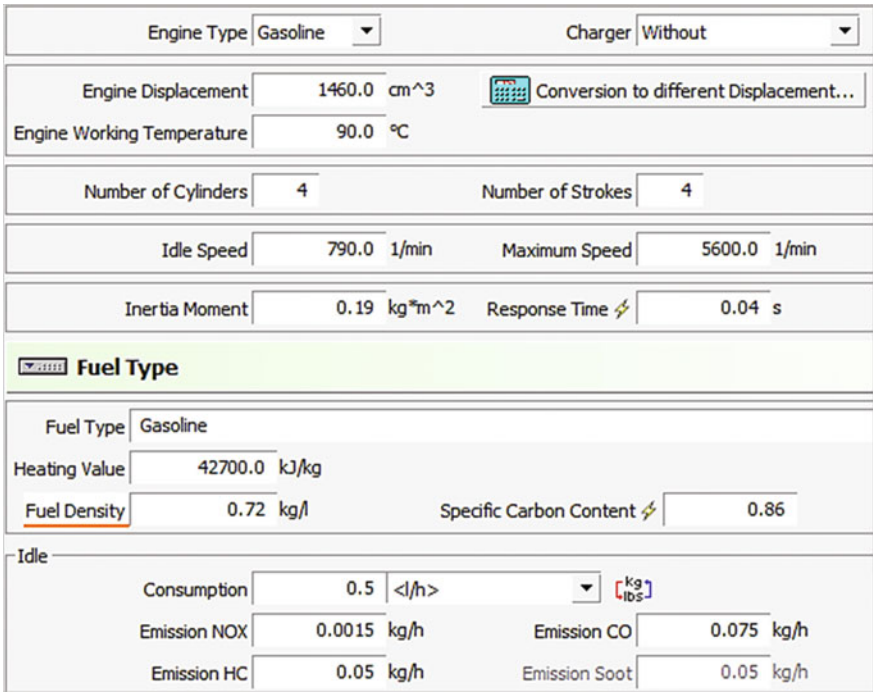


Fig. 5.4 IC Engine input data specifications window

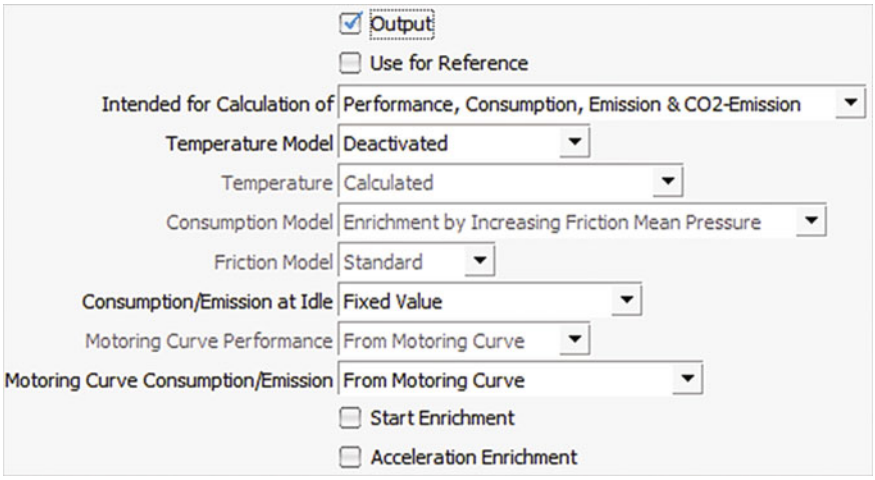


Fig. 5.5 Properties of IC Engine

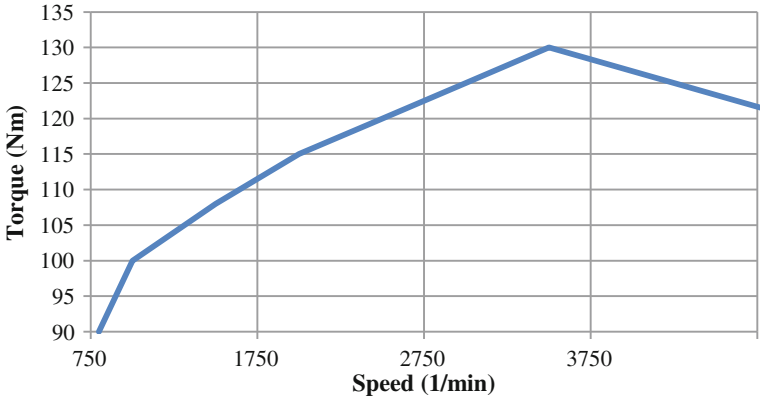


Fig. 5.6 Full Load Characteristic

Table 5.4 Full Load Characteristic data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
800	90	2500	120
1000	100	3000	125
1500	108	3500	130
2000	115	5000	120

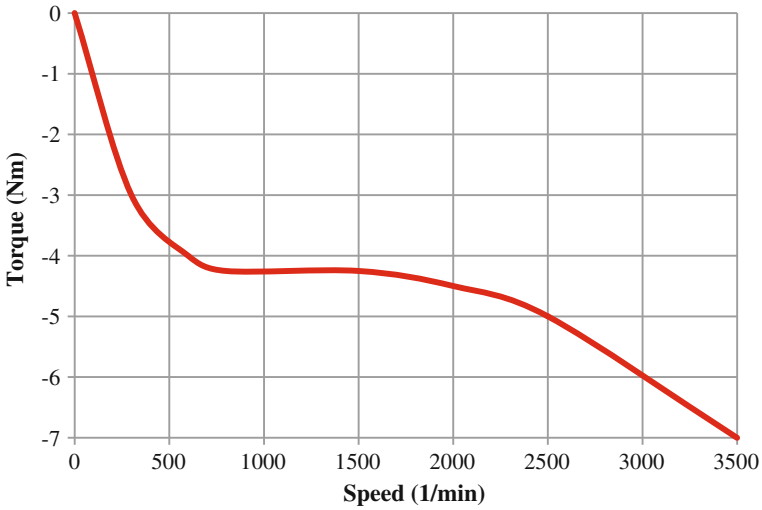


Fig. 5.7 Motoring Curve

Table 5.5 Motoring Curve data

Speed (1/min)	Torque (Nm)
0	0.00
300	−3.00
600	−4.00
800	−4.25
1500	−4.25
2000	−4.50
2500	−5.00
3500	−7.00

Table 5.6 Fuel Consumption Map data

(a)											
850	(b)	−4.0	−0.5	0.0	1.60	3.16	4.55	5.95	7.32	8.63	9.30
	(c)	0.60	0.62	0.71	1.02	1.32	1.64	1.95	2.34	2.76	3.15
1250	(b)	−4.0	−0.5	0.0	0.19	1.82	3.32	4.73	7.59	8.90	10.9
	(c)	0.73	0.82	0.90	0.96	1.42	1.88	2.37	3.35	3.96	4.54
1700	(b)	−4.0	−0.5	0.0	2.06	3.54	4.89	6.33	7.83	10.9	12.3
	(c)	1.00	1.05	1.14	1.86	2.48	3.07	3.69	4.34	6.29	7.08
2300	(b)	−4.0	−0.5	0.0	2.30	3.07	5.25	6.71	9.63	12.3	14.3
	(c)	1.45	1.50	1.56	2.83	3.34	4.61	5.47	7.34	9.51	11.6
2900	(b)	−4.0	−0.5	0.0	0.71	3.97	5.49	8.41	9.81	11.3	14.8
	(c)	1.70	1.78	1.93	2.40	4.63	5.68	7.77	8.87	10.0	14.1
3500	(b)	−4.0	−0.5	0	2.41	3.97	7.04	8.59	10.3	13.4	15.1
	(c)	2.10	2.15	2.40	4.26	5.65	8.12	9.54	11.1	14.5	16.9
4200	(b)	−4.0	−0.5	0	2.31	3.82	5.34	8.53	9.99	13.1	15.1
	(c)	2.65	2.75	2.92	5.04	6.56	8.02	11.2	12.8	17.6	21.7
5100	(b)	−4.0	−0.5	0	3.62	5.10	8.12	9.77	11.2	12.5	14.5
	(c)	3.65	3.78	3.99	8.30	10.0	14.0	16.7	19.2	22.6	28.2
6000	(b)	−4.0	−0.5	0	2.76	4.18	5.53	8.39	9.72	10.9	13.1
	(c)	4.80	4.95	5.17	9.24	11.4	13.5	19.0	22.7	26.1	32.7

the field of potential driving conditions (Fig. 5.14). With the model of the CVT gearbox it is possible to change the transmission between two user-defined threshold values. The adjusting speed between different transmissions is internal fixed at a constant value [2].

To define component input data (Table 5.11) double click on the icon and select edit to open the following window. The efficiency fixed curve can be defined as function of the transmission ratio (Fig. 5.15).

Final Drive (5) or **Single Ratio Transmission** is a gear step with fixed ratio. It can be used as a transmission step of the differential (Fig. 5.16).

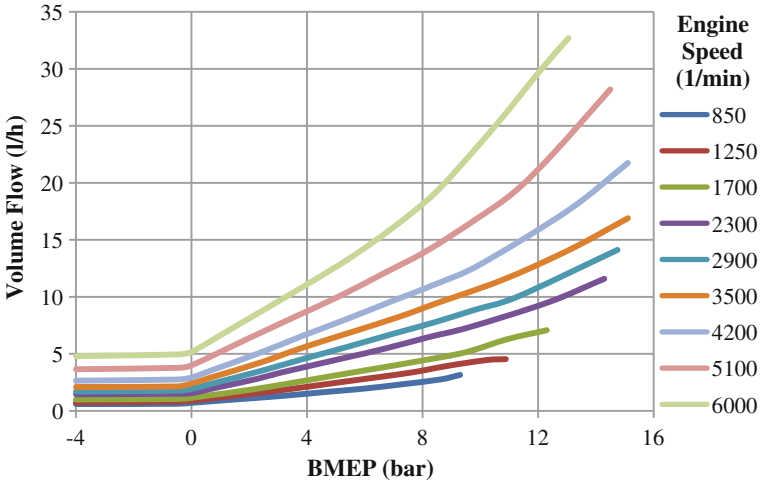


Fig. 5.8 Fuel Consumption Map

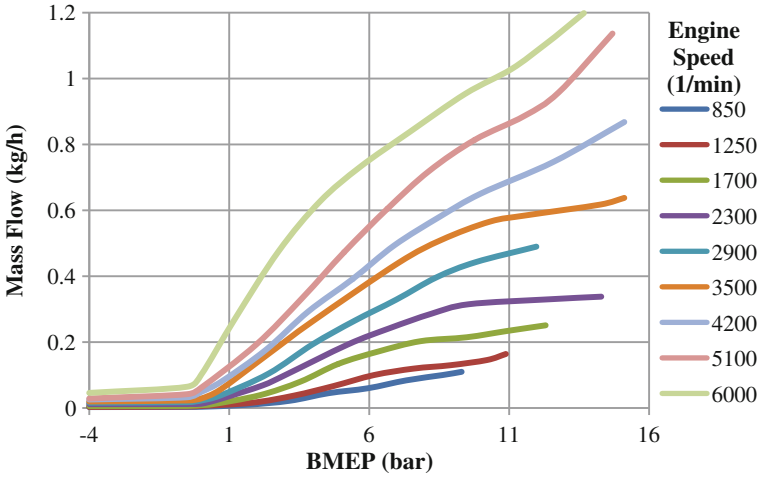


Fig. 5.9 NO_x emission map

To define component input data double click on the final drive icon and enter the following data (Table 5.12).

The **Wheels** and **Tires** link the vehicle to the road. The wheel component considers many influencing variables and their effect on the rolling state (Fig. 5.17).

Information data for the four wheels is the same (Vehicle Front Right (6), Vehicle Front Left (7), Vehicle Rear Right (8), and Vehicle Rear Left (9)). Double click on the wheel and enter the following data (Table 5.13) [1].

Table 5.7 NO_x emission map data

(a)											
850	(b)	−4.0	−0.5	0.00	1.61	3.16	4.55	5.95	7.32	8.62	9.30
	(c)	0.00	0.00	0.00	0.01	0.02	0.05	0.06	0.08	0.10	0.11
1250	(b)	−4.0	−0.5	0.00	1.82	3.32	4.73	6.17	8.90	10.2	10.9
	(c)	0.00	0.01	0.01	0.02	0.04	0.07	0.10	0.13	0.15	0.16
1700	(b)	−4.0	−0.5	0.00	0.42	2.08	4.89	7.83	9.48	10.1	12.3
	(c)	0.01	0.01	0.01	0.01	0.04	0.13	0.20	0.22	0.23	0.25
2300	(b)	−4.0	−0.5	0.00	0.73	2.20	5.24	8.21	9.55	12.4	14.3
	(c)	0.01	0.01	0.01	0.03	0.07	0.19	0.29	0.32	0.33	0.34
2900	(b)	−4.0	−0.5	0.00	0.70	2.41	5.47	8.41	9.81	12.0	15.2
	(c)	0.02	0.02	0.02	0.04	0.11	0.27	0.40	0.44	0.49	0.58
3500	(b)	−4.0	−0.5	0.00	0.68	2.41	7.05	8.59	11.6	14.3	15.1
	(c)	0.02	0.02	0.03	0.06	0.17	0.44	0.51	0.59	0.62	0.64
4200	(b)	−4.0	−0.5	0.00	0.75	2.31	5.41	8.53	9.99	12.6	15.1
	(c)	0.03	0.03	0.05	0.08	0.18	0.39	0.58	0.65	0.75	0.87
5100	(b)	−4.0	−0.5	0.00	1.97	3.62	6.65	9.77	11.5	12.8	14.7
	(c)	0.03	0.04	0.06	0.19	0.34	0.61	0.81	0.89	0.96	1.14
6000	(b)	−4.0	−0.5	0.00	1.21	2.76	5.68	9.43	12.3	13.5	14.2
	(c)	0.05	0.07	0.10	0.27	0.48	0.73	0.95	1.11	1.18	1.23

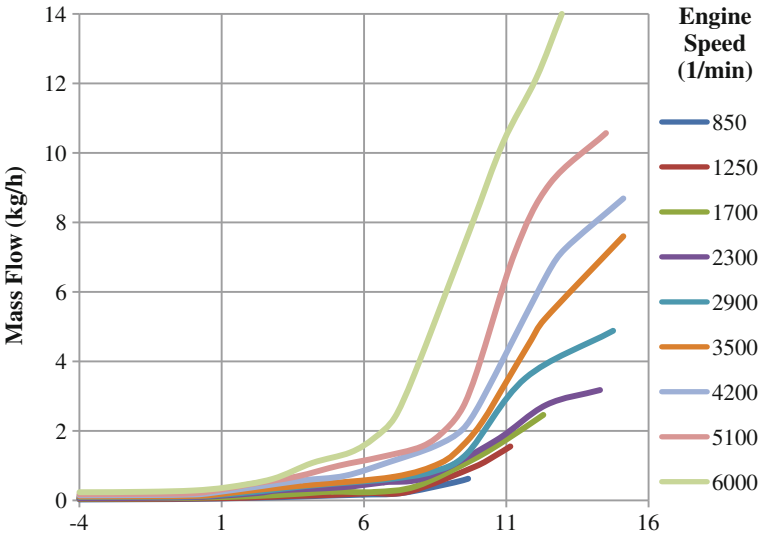


Fig. 5.10 CO emission map

Table 5.8 CO emission map data

(a)											
850	(b)	−4.0	−1.6	0.00	1.60	3.16	4.55	5.95	7.32	9.18	9.66
	(c)	0.03	0.03	0.04	0.07	0.10	0.13	0.17	0.21	0.52	0.62
1250	(b)	−4.0	−1.7	0.00	1.82	4.73	6.16	7.59	9.89	10.6	11.1
	(c)	0.04	0.04	0.06	0.08	0.15	0.21	0.25	0.97	1.28	1.55
1700	(b)	−4.0	−1.7	0.00	2.06	4.89	6.37	7.83	9.82	11.0	12.3
	(c)	0.05	0.06	0.08	0.12	0.25	0.24	0.41	1.17	1.76	2.46
2300	(b)	−4.0	−1.7	0.00	0.73	2.30	5.22	8.21	10.6	12.4	14.3
	(c)	0.06	0.07	0.09	0.12	0.21	0.38	0.67	1.72	2.74	3.17
2900	(b)	−4.0	−1.7	0.00	0.85	2.42	5.52	8.42	9.62	11.7	14.8
	(c)	0.10	0.10	0.12	0.15	0.27	0.52	0.83	1.35	3.52	4.88
3500	(b)	−4.0	−1.7	0.00	0.72	2.41	7.04	10.2	11.9	12.3	15.1
	(c)	0.11	0.12	0.13	0.16	0.32	0.68	2.28	4.62	5.21	7.60
4200	(b)	−4.0	−1.7	0.00	0.72	3.82	6.88	9.48	10.1	13.1	15.1
	(c)	0.15	0.15	0.17	0.22	0.57	1.10	2.05	2.85	7.24	8.69
5100	(b)	−4.0	−1.7	0.00	1.00	3.62	6.55	8.86	9.48	11.3	12.5
	(c)	0.18	0.19	0.21	0.31	0.68	1.24	2.03	2.69	7.14	9.11
6000	(b)	−4.0	−1.7	0.00	1.21	4.18	6.35	7.77	9.72	12.1	13.1
	(c)	0.24	0.25	0.29	0.38	1.08	1.79	3.63	7.78	12.2	14.2

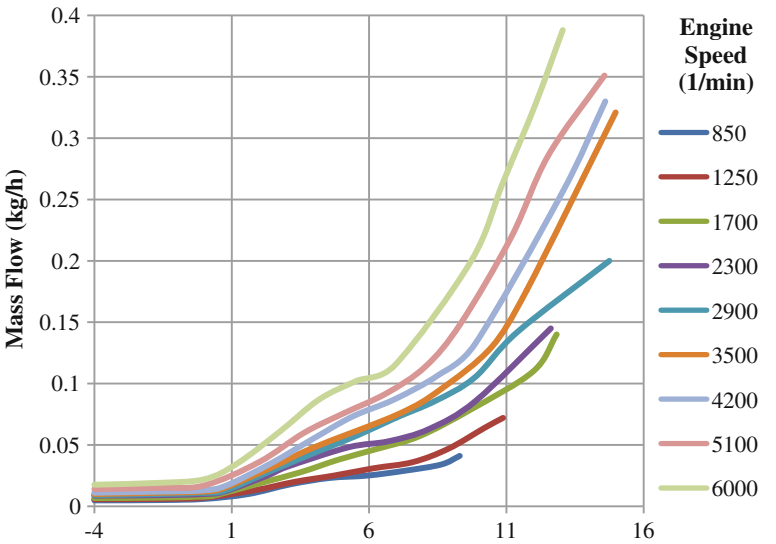


Fig. 5.11 HC emission map

Table 5.9 HC emission map data

(a)											
850	(b)	−4.0	−1.6	0.00	1.60	3.16	4.55	5.95	7.32	8.63	9.30
	(c)	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04
1250	(b)	−4.0	−1.6	0.00	1.82	3.32	4.73	6.17	7.60	8.90	10.9
	(c)	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.05	0.07
1700	(b)	−4.0	−1.6	0.00	3.54	4.89	6.33	7.83	9.72	11.9	12.8
	(c)	0.01	0.01	0.01	0.03	0.04	0.05	0.06	0.08	0.11	0.14
2300	(b)	−4.0	−1.6	0.00	0.73	2.30	5.25	6.71	9.89	12.6	14.8
	(c)	0.01	0.01	0.01	0.01	0.03	0.05	0.05	0.09	0.15	0.18
2900	(b)	−4.0	−1.6	0.00	0.79	2.45	5.60	6.97	9.85	11.4	14.8
	(c)	0.01	0.01	0.01	0.01	0.03	0.06	0.07	0.11	0.14	0.20
3500	(b)	−4.0	−1.6	0.00	0.74	2.49	7.06	8.59	10.5	11.7	15.0
	(c)	0.01	0.01	0.01	0.02	0.03	0.08	0.10	0.13	0.18	0.32
4200	(b)	−4.0	−1.6	0.00	2.43	3.89	5.38	6.91	9.85	13.0	14.6
	(c)	0.01	0.01	0.01	0.04	0.05	0.07	0.09	0.13	0.26	0.33
5100	(b)	−4.0	−1.6	0.00	3.64	5.10	6.63	8.06	11.2	12.5	14.6
	(c)	0.01	0.02	0.02	0.06	0.08	0.09	0.11	0.22	0.29	0.35
6000	(b)	−4.0	−1.6	0.00	2.76	4.18	5.53	6.94	10.9	12.1	13.1
	(c)	0.02	0.02	0.02	0.06	0.09	0.10	0.12	0.26	0.33	0.39

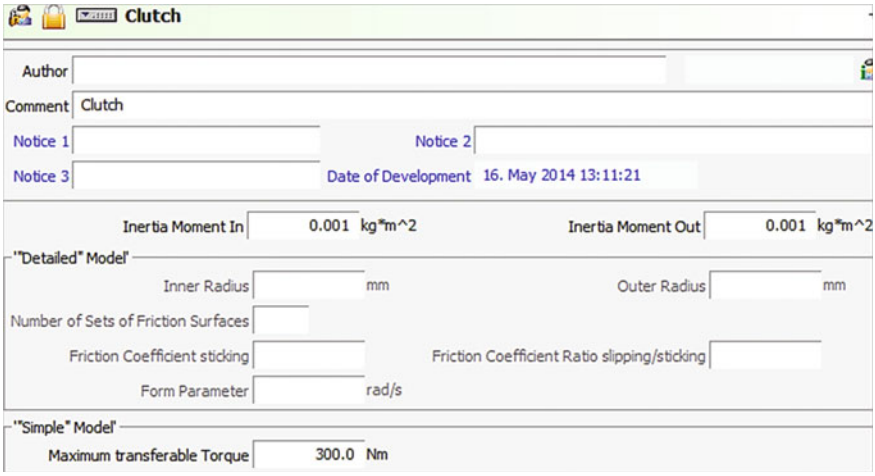


Fig. 5.12 Clutch input data specifications window

The **Brake** component is described by brake data and dimensions (Fig. 5.18). It is possible to define drum brakes as well as disk brakes.

Input data for the two front brakes is the same and also the data for the two rear brakes is the same (Rear Drum Brake Right (10), Front Disk Brake Right (11), Rear

Table 5.10 Clutch input data

Name	Value	Unit
Inertia Moment In	0.001	kg m^2
Inertia Moment Out	0.001	kg m^2
Clutch Release	0.000	%
Pressure Force	6000	N
Clutch Release	100	%
Pressure Force	0.000	N
Maximum transferable Torque	300	Nm

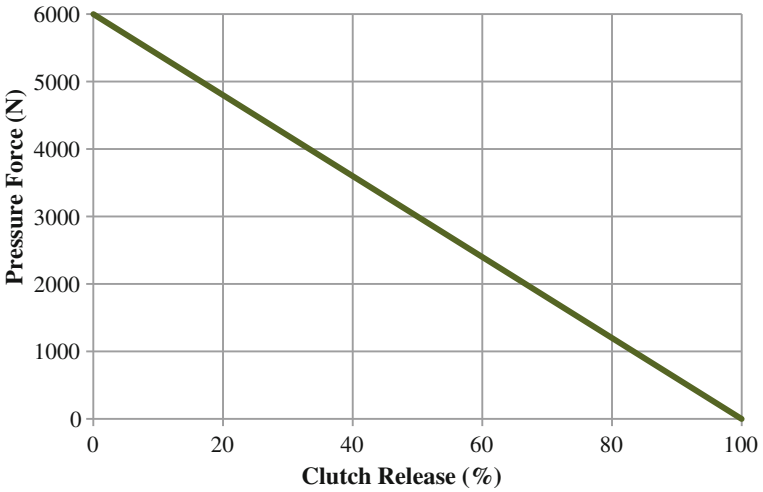


Fig. 5.13 Pressure force

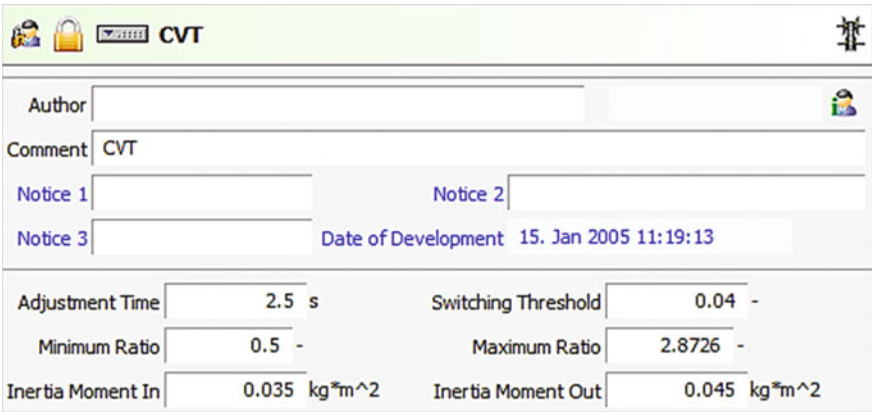


Fig. 5.14 CVT input data specifications window

Table 5.11 CVT input data

Name	Value	Unit
Inertia Moment In	0.035	kg m^2
Inertia Moment Out	0.045	kg m^2
Adjustment Time	2.500	s
Minimum Ratio	0.500	–
Switching Threshold	0.040	–
Maximum Ratio	2.873	–

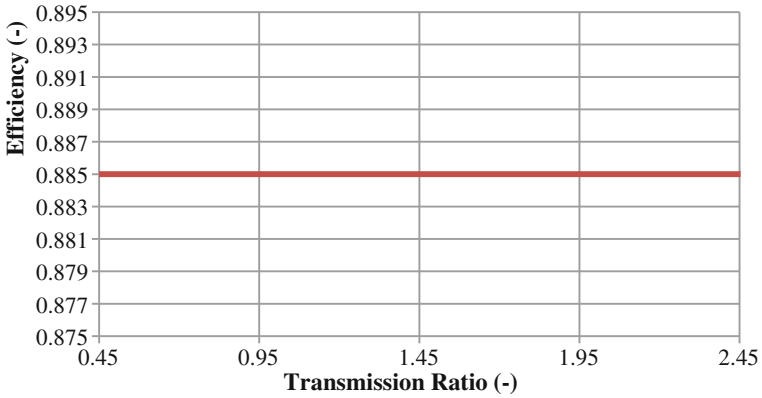


Fig. 5.15 Efficiency fixed

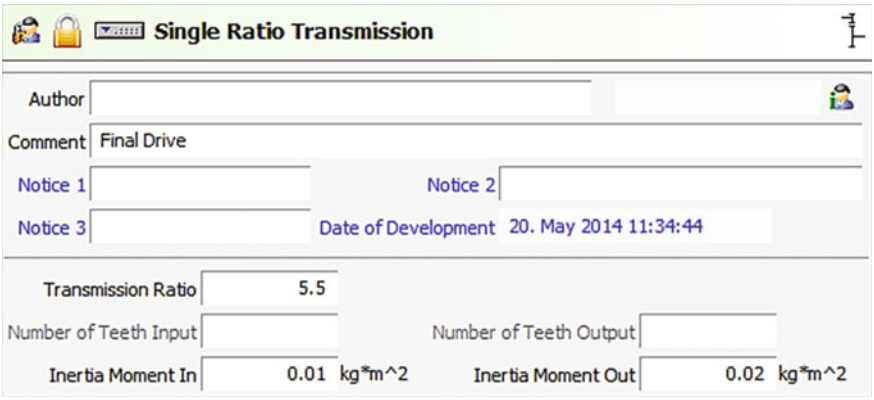


Fig. 5.16 Final Drive input data specifications window

Table 5.12 Final Drive input data

Name	Value	Unit
Inertia Moment In	0.01	kg m^2
Inertia Moment Out	0.02	kg m^2
Transmission Ratio	5.50	–
Efficiency	0.90	–

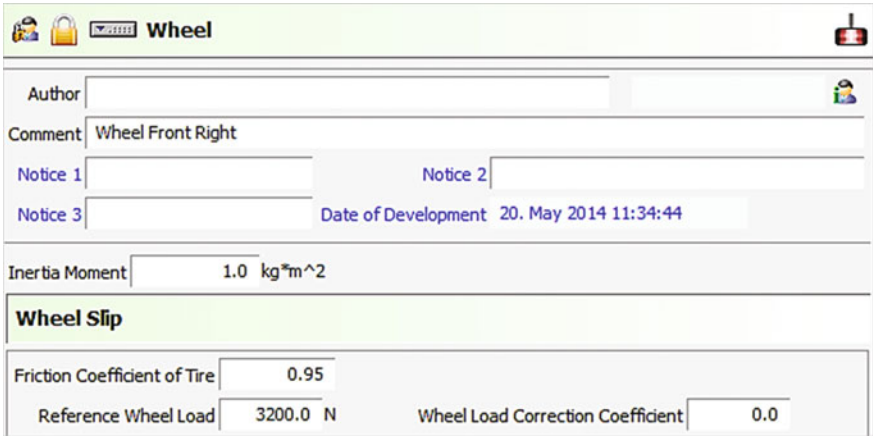


Fig. 5.17 Wheels input data specifications window

Table 5.13 Wheels input data

Name	Value	Unit
Wheel Inertia Moment	1.000	kg m^2
Friction Coefficient of Tire	0.950	–
Reference Wheel Load	3200.0	N
Wheel Load Correction Coefficient	0.000	–
Static Rolling Radius	290.0	mm
Circumference	1822.12	mm
Dynamic Rolling Radius	310.0	mm
Circumference	1947.79	mm

Drum Brake Left (12), and Front Disk Brake Left (13)). Double click on the brake icon and enter the following data (Table 5.14).

Using **E-Machine** component (14) together with the battery H, the user can simulate hybrid systems. The model of the electric machine contains two components, the inverter and the electric motor. For this type of model a characteristic map for the efficiency is used to calculate the loss of power. The thermic model takes the warm up of the electric machine into account regarding the occurring losses. The

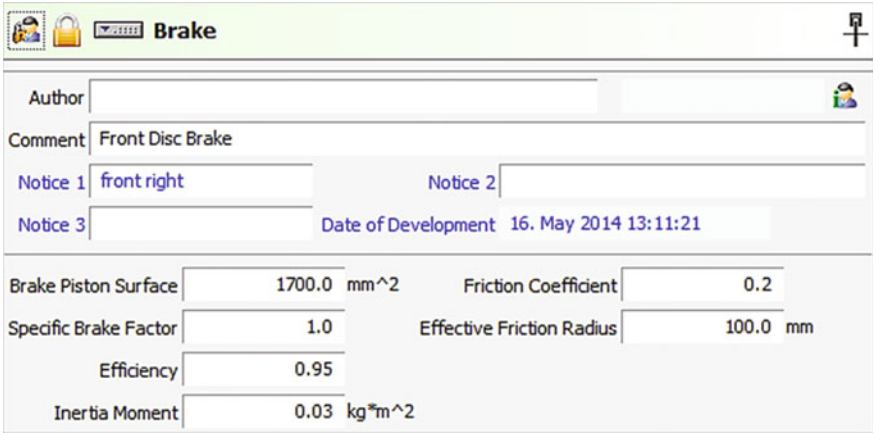


Fig. 5.18 Brake input data specifications window

Table 5.14 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	1700.0	500.0	1700.0	500.0	mm^2
Specific Factor	1.000	2.500	1.000	2.500	–
Efficiency	0.950	0.950	0.950	0.950	–
Inertia Moment	0.030	0.030	0.030	0.030	$kg\ m^2$
Friction Coefficient	0.200	0.200	0.200	0.200	–
Friction Radius	100.0	90.00	100.0	90.00	mm

warm up of the environment with respect to the cooling system due to the electric machine is not considered in the electric machine component.

The maximal power should be restricted to avoid exceeding the given limit for the temperature due to the occurring losses. Therefore, the permissible losses are dependent on the actual temperature of the motor and the maximal moment of inertia is determined according to these values [2].

Double click on the e-machine icon and enter the following data (Fig. 5.19).

The value of the voltage level should be entered at which the following characteristic maps of the machine have been measured. In addition to the U1 level (Fig. 5.20 and Table 5.15) the U2 level (Fig. 5.21 and Table 5.16) will be activated in the property window.

For each level the corresponding voltage value must be defined and the corresponding characteristic maps (voltage for U1 = 80 V, voltage for U1 = 280 V). The maximum mechanical (power) torque is defined as a function of the machine speed (a—speed (1/min), b—torque (Nm)) [1].

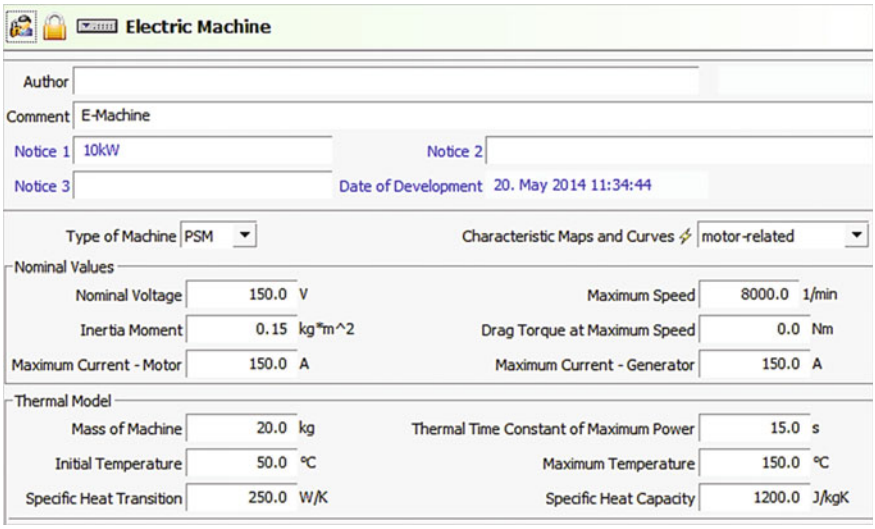


Fig. 5.19 E-Machine input data specifications window

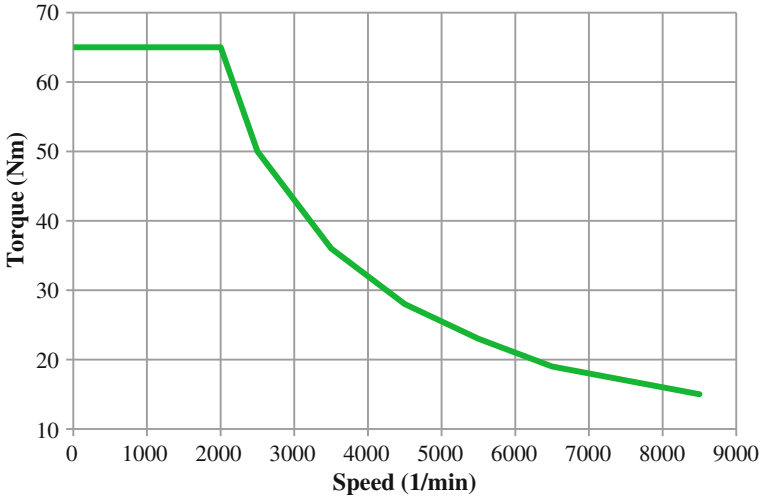


Fig. 5.20 Maximum mechanical torque variation U1

Table 5.15 Maximum mechanical torque variation U1

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
0	65	4500	28
2000	65	5500	23
2500	50	6500	19
3500	36	8500	15

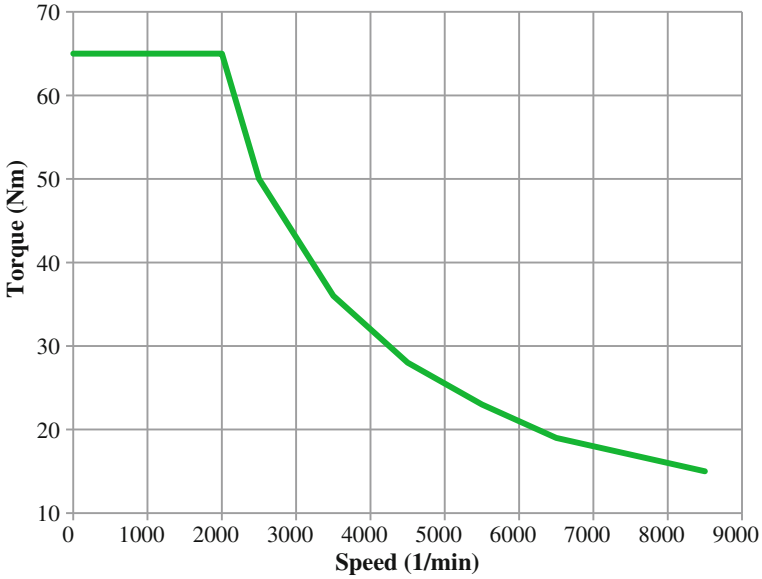


Fig. 5.21 Maximum mechanical torque variation U2

Table 5.16 Maximum mechanical torque variation U2

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
0	65	4500	28
2000	65	5500	23
2500	50	6500	19
3500	36	8500	15

The efficiency curve can be defined as function of the maximum mechanical torque (Fig. 5.22 and Table 5.17) [1].

The **Differential** (15) is a particular type of simple planetary gear train that has the property that the angular velocity of its carrier is the average of the angular velocities of its sun and annular gears (Fig. 5.23). To define component input data double click on the differential icon and enter the following data (Table 5.18).

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component. All mechanical connections starting from the selected component are shown in a tree structure in the left side of the window (Fig. 5.24—Electric Machine, Fig. 5.25—Gasoline Engine).

The **Cockpit** (16) links the driver and the vehicle (Fig. 5.26). In this component connections are only made via the Data Bus. The pedal positions are transferred into corresponding indicators via the pedal characteristics (Table 5.19).

To define the input data click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)), clutch pedal characteristic

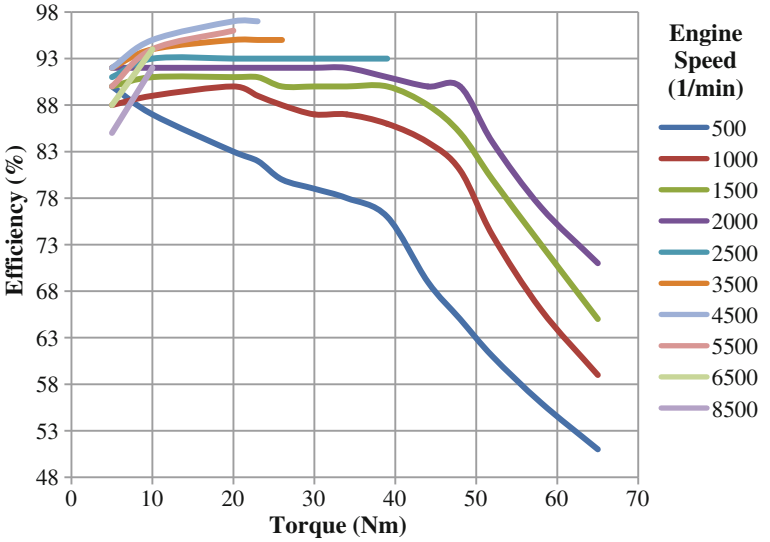


Fig. 5.22 Efficiency curves

Table 5.17 Efficiency curve data

(a)														
500	(b)	5	10	20	23	26	30	34	39	44	48	52	58	65
	(c)	90	87	83	82	80	79	78	76	69	65	61	56	51
1000	(b)	5	10	20	23	26	30	34	39	44	48	52	58	65
	(c)	88	89	90	89	88	87	87	86	84	81	74	66	59
1500	(b)	5	10	20	23	26	30	34	39	44	48	52	58	65
	(c)	90	91	91	91	90	90	90	90	88	85	80	73	65
2000	(b)	5	10	20	23	26	30	34	39	44	48	52	58	65
	(c)	92	92	92	92	92	92	92	91	90	90	84	77	71
2500	(b)	5	10	20	23	26	30	34	39	–	–	–	–	–
	(c)	91	93	93	93	93	93	93	93	–	–	–	–	–
3500	(b)	5	10	20	23	26	–	–	–	–	–	–	–	–
	(c)	92	94	95	95	95	–	–	–	–	–	–	–	–
4500	(b)	5	10	20	23	–	–	–	–	–	–	–	–	–
	(c)	92	95	97	97	–	–	–	–	–	–	–	–	–
5500	(b)	5	10	20	–	–	–	–	–	–	–	–	–	–
	(c)	90	94	96	–	–	–	–	–	–	–	–	–	–
6500	(b)	5	10	–	–	–	–	–	–	–	–	–	–	–
	(c)	88	94	–	–	–	–	–	–	–	–	–	–	–
8500	(b)	5	10	–	–	–	–	–	–	–	–	–	–	–
	(c)	85	92	–	–	–	–	–	–	–	–	–	–	–

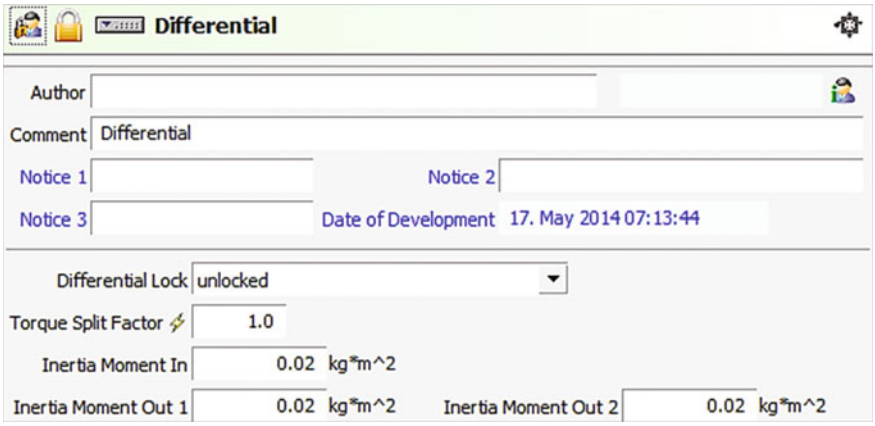


Fig. 5.23 Differential input data specifications window

Table 5.18 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.000	–
Inertia Moment In	0.020	kg m^2
Inertia Moment Out1	0.020	kg m^2
Inertia Moment Out2	0.020	kg m^2

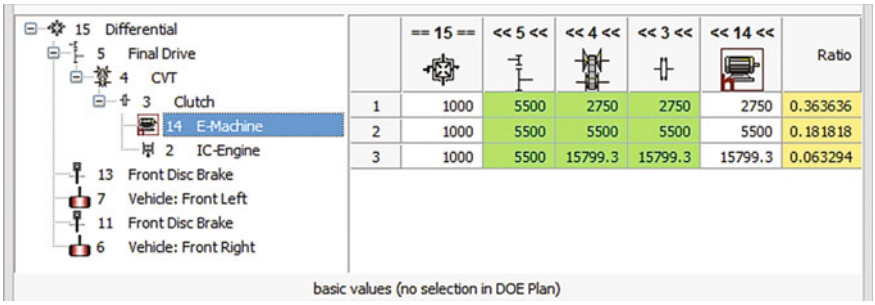


Fig. 5.24 Kinematic Chain Browser e-machine component

(a—clutch pedal travel (%), b—clutch release (%)), and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data for all (Fig. 5.27).

The **CVT Control** (17) is an easy way to provide target transmission considering the velocity and the engine load (Fig. 5.28). In addition it is possible to control a clutch. To define component input data double click on the CVT control icon and enter the following data (Table 5.20).

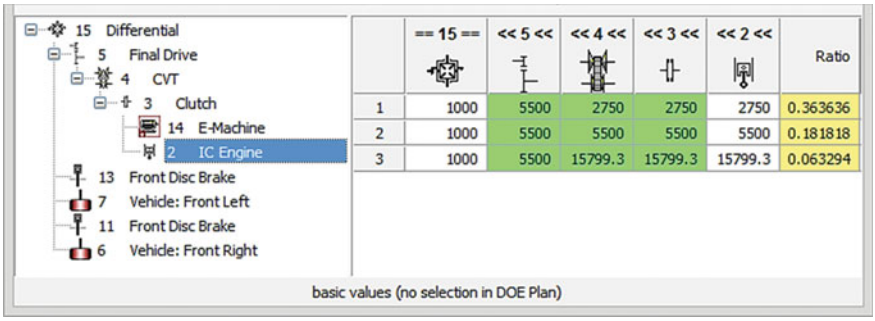


Fig. 5.25 Kinematic Chain Browser IC Engine component

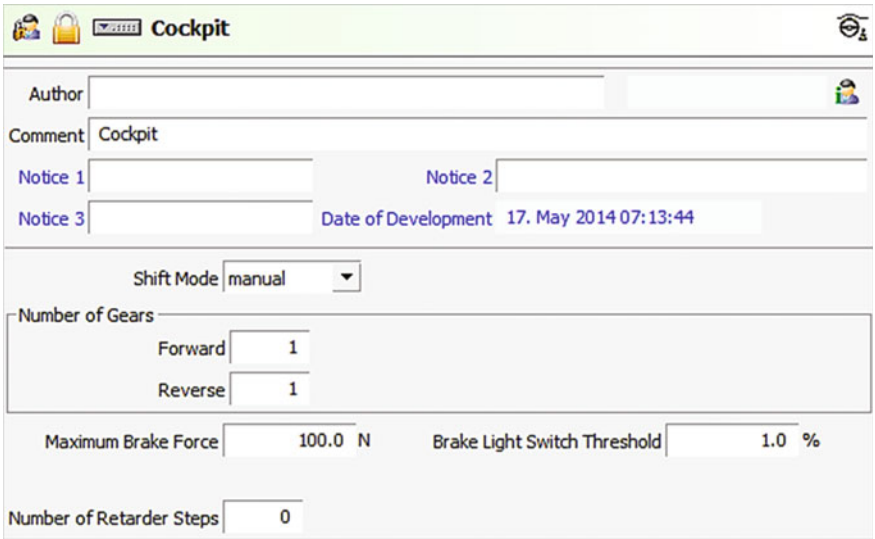


Fig. 5.26 Cockpit input data specifications window

Table 5.19 Cockpit input data

Name	Value	Unit
Shift Mode	Manual	–
Number of Gears Forward	1.000	–
Number of Gears Back	1.000	–
Maximum Brake Force	100.0	N
Brake Light Switch Threshold	1.000	%
Number of Retarder Steps	0.000	–

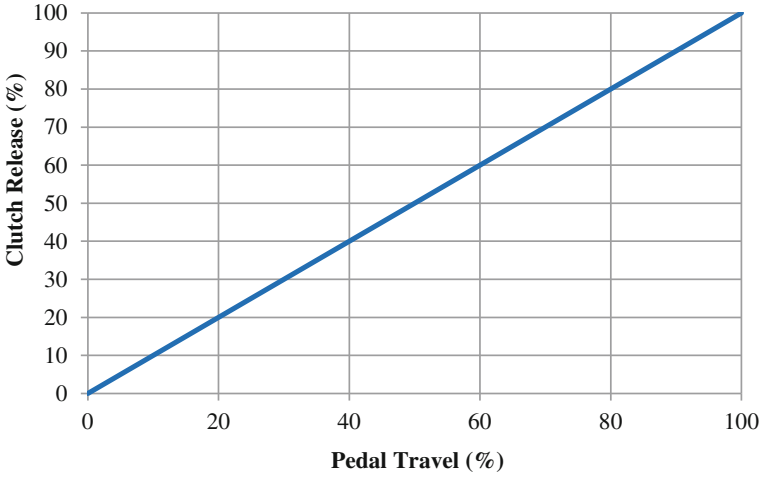


Fig. 5.27 Pedal characteristic

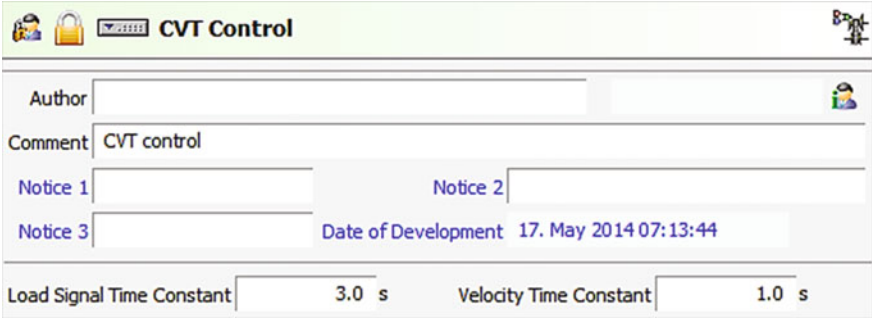


Fig. 5.28 CVT control input data specifications window

Table 5.20 CVT control input data

Name	Value	Unit
Load Signal Time Constant	3.0	s
Velocity Time Constant	1.0	s

The desired transmission ratio (Fig. 5.29 and Table 5.21) can be defined as a function of a—velocity (m/s), b—load signal (%), and c—transmission ratio (−).

The desired clutch release (Fig. 5.30 and Table 5.22) of the starting clutch can be defined as a function of a—speed (1/min), b—load signal (%), and c—clutch release (%) [3].

The **Battery H** (18) component is used for simulating hybrid and electric vehicles. The basic model consists of a voltage source and an ohmic resistance (Fig. 5.31) [2].

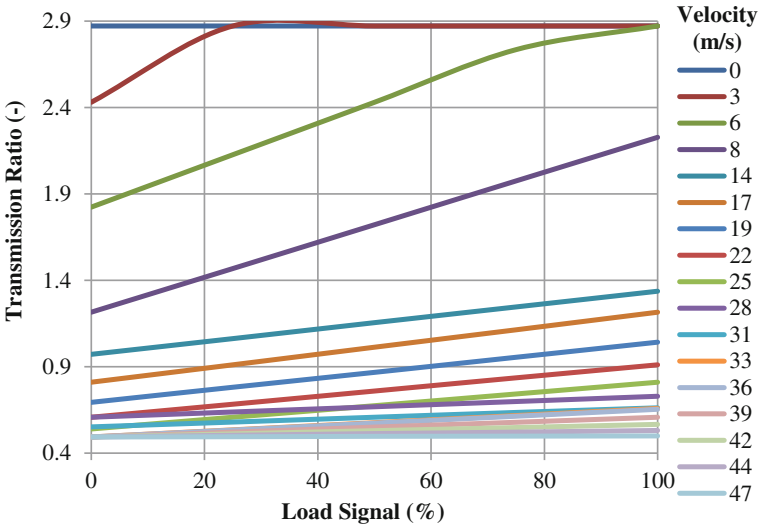


Fig. 5.29 Desired transmission ratio

Table 5.21 Desired transmission ratio data

(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
0	0	2.9	6	0	1.8	11	0	1.2	17	0	0.8	22	0	0.6
0	25	2.9	6	25	2.1	11	25	1.0	17	25	0.9	22	25	0.7
0	50	2.9	6	50	2.4	11	50	1.1	17	50	1.0	22	50	0.8
0	75	2.9	6	75	2.7	11	75	1.3	17	75	1.1	22	75	0.8
0	100	2.9	6	100	2.9	11	100	1.7	17	100	1.2	22	100	0.9
3	0	2.4	8	0	1.2	14	0	1.0	19	0	0.7	25	0	0.5
3	25	2.9	8	25	1.5	14	25	1.1	19	25	0.8	25	25	0.6
3	50	2.9	8	50	1.7	14	50	1.2	19	50	0.9	25	50	0.7
3	75	2.9	8	75	2.0	14	75	1.3	19	75	1.0	25	75	0.7
3	100	2.9	8	100	2.2	14	100	1.4	19	100	1.0	25	100	0.8
(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)			
28	0	0.6	33	0	0.5	39	0	0.5	44	0	0.5			
28	25	0.6	33	25	0.5	39	25	0.5	44	25	0.5			
28	50	0.7	33	50	0.6	39	50	0.6	44	50	0.5			
28	75	0.7	33	75	0.6	39	75	0.6	44	75	0.5			
28	100	0.7	33	100	0.7	39	100	0.6	44	100	0.5			
31	0	0.6	36	0	0.5	42	0	0.5	47	0	0.5			
31	25	0.6	36	25	0.5	42	25	0.5	47	25	0.5			
31	50	0.6	36	50	0.6	42	50	0.5	47	50	0.5			
31	75	0.6	36	75	0.6	42	75	0.5	47	75	0.5			
31	100	0.7	36	100	0.7	42	100	0.6	47	100	0.5			

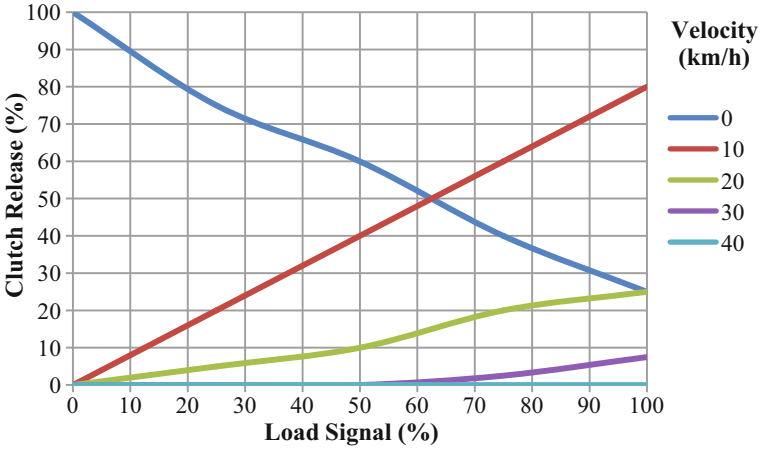


Fig. 5.30 Desired clutch release

Table 5.22 Desired clutch release data

(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
0	0	100	20	0	0	40	0	0	100	0	0	150	0	0
0	25	75	20	25	5	40	100	0	100	100	0	150	100	0
0	50	60	20	50	10	50	0	0	110	0	0	160	0	0
0	75	40	20	75	20	50	100	0	110	100	0	160	100	0
0	100	25	20	100	25	60	0	0	120	0	0	170	0	0
10	0	0	30	0	0	60	100	0	120	100	0	170	100	0
10	25	20	30	25	0	80	0	0	130	0	0	–	–	–
10	50	40	30	50	0	80	100	0	130	100	0	–	–	–
10	75	60	30	75	2.5	90	0	0	140	0	0	–	–	–
10	100	80	30	100	7.5	90	100	0	140	100	0	–	–	–

Double click on the battery H icon and enter the following data (Table 5.23). The resistance is constructed in a way that a big part of the complex processes within the battery are taken into consideration. 2 RC elements which describe the concentration overvoltage and the transfer overvoltage can be added optionally.

The thermal behavior of the battery H is described by a thermal substitution model. The warming caused by the losses inside the battery H and the cooling caused by convection is taken into consideration.

Single cells can be modelled as well as any combination of cells. Therefore, the user can construct any desired model.

The idle voltage—charge (b) is the idle voltage of one cell in charge mode. There is no electrical consumer; it is a function of the State of Charge SOC (a) (Fig. 5.32 and Table 5.24).

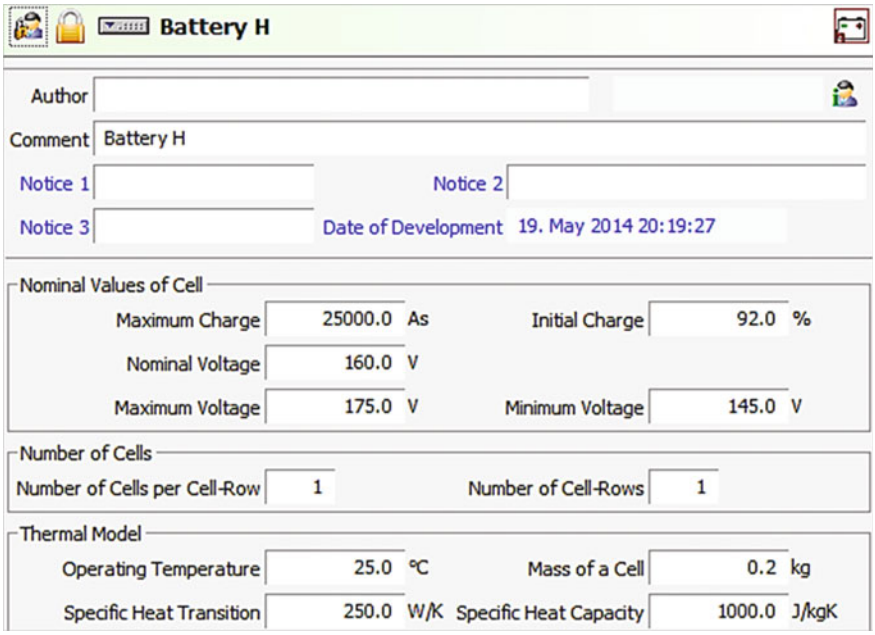


Fig. 5.31 Battery H input data specifications window

Table 5.23 Battery H input data

Name	Value	Unit
Maximum Charge	25,000	As
Nominal Voltage	160.00	V
Maximum Voltage	175.00	V
Initial Charge	92.00	%
Minimum Voltage	145.0	V
Number of Cells per Cell-Row	1.000	–
Number of Cell-Row	1.000	–
Operating Temperature	25.00	°C
Mass of a Cell	0.200	kg
Specific Heat Transition	250.0	W/K
Specific Heat Capacity	1000	J/kg K
Internal Resistance	0.600	Ω

The Idle voltage—discharge (b) of one cell is the voltage without an electrical consumer, there is no flow of current, and it is a function of the State of Charge SOC (a) (Fig. 5.33 and Table 5.25).

MATLAB® DLL (19) Engineering Measurement System (EMS) interface allows to integrate controllers and/or mechanical elements, such as special drives, which have been created using MATLAB®/Simulink™, into the computational

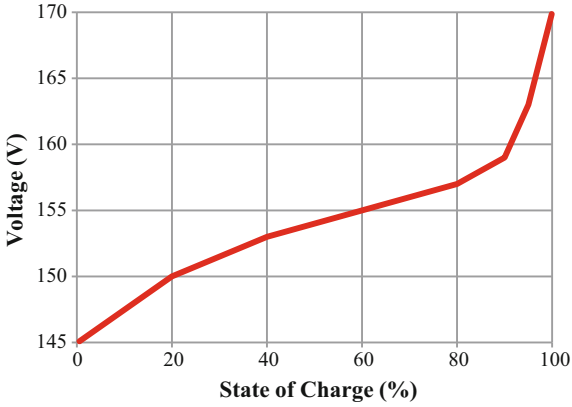


Fig. 5.32 Idle voltage charge

Table 5.24 Idle voltage—charge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	145	80	157
20	150	90	159
40	153	95	163
60	155	100	170

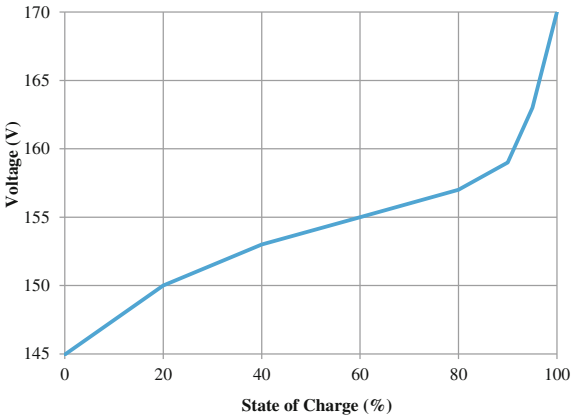


Fig. 5.33 Idle voltage discharge

model of AVL CRUISE. If an element is created and parameterized under Simulink™, it will be compiled to a so-called Dynamic Link Library (DLL) under Windows. These files will be integrated into AVL CRUISE. The advantage of this

Table 5.25 Idle voltage—discharge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	145	80	157
20	150	90	159
40	153	95	163
60	155	100	170

procedure is that AVL CRUISE itself does not need to be compiled again if MATLAB®/Simulink™ modules are to be integrated (Fig. 5.34) [2].

The input and output variables will be transferred by means of in-ports and out-ports. These ports create the interface to the MATLAB® module and are available at the AVL CRUISE Data Bus.

The compiled DLL file will be loaded from folder: project/version/userdata/_CRUISE_R121_ctrl_3_DLL.dll.

The input values are transferred to the MATLAB® function. From the module, the results are received and input to the output channels (Table 5.26).

The **Delta Torque Combustion Engine** (20) component is a function used to calculate with user-defined functions, in this case the adaption of the acceleration pedal for the IC Engine with Integrated Starter Generator (ISG).

The Integrated Starter Generator (ISG) merges both the conventional starter and generator of an automobile in a single electric device. The ISG produces electric power when the vehicle is running, which is used to supply electric devices and to charge the battery.

The ISG can help to decelerate the vehicle by generating electric power, which is called regenerative braking. The electric power generated charges the battery, reducing fuel consumption. If a clutch disconnects the ISG and the compressor from the engine during the idle stop, the ISG can drive the air-conditioning compressor via a belt [2].

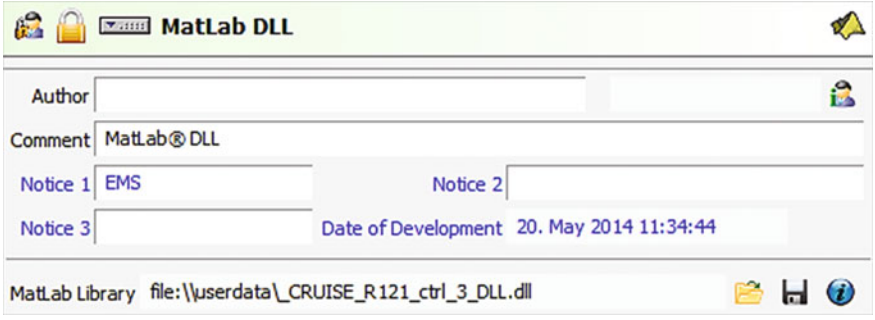


Fig. 5.34 MATLAB® DLL input data specifications window

Table 5.26 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
Inport 0	Engine Speed	rad/s	Optional	0
Inport 1	Torque behind Flywheel	Nm	Optional	0
Inport 2	Load Signal	–	Optional	0
Inport 3	Brake Pressure	Pa	Optional	0
Inport 4	Velocity	m/s	Optional	0
Inport 5	Battery Charge	As	Optional	0
Inport 6	Start Switch	–	Optional	0
Inport 7	Current Transmission Ratio	–	Optional	0
Inport 8	Actual Clutch Release	–	Optional	0
Inport 9	Current	A	Optional	0
Outport 0	Start Switch	–	Optional	0
Outport 1	Load Signal—EMS	–	Optional	0
Outport 2	Load Signal	–	Optional	0
Outport 3	Brake Pressure—EMS	Pa	Optional	0

To define component input data double click on the delta torque combustion engine icon and enter the following data for function (Fig. 5.35), and for description of Data Bus (Table 5.27).

The **Delta Torque Brake** (21) component is a function used to calculate (with user-defined functions), the adaption brake pedal for mechanical brake with ISG.

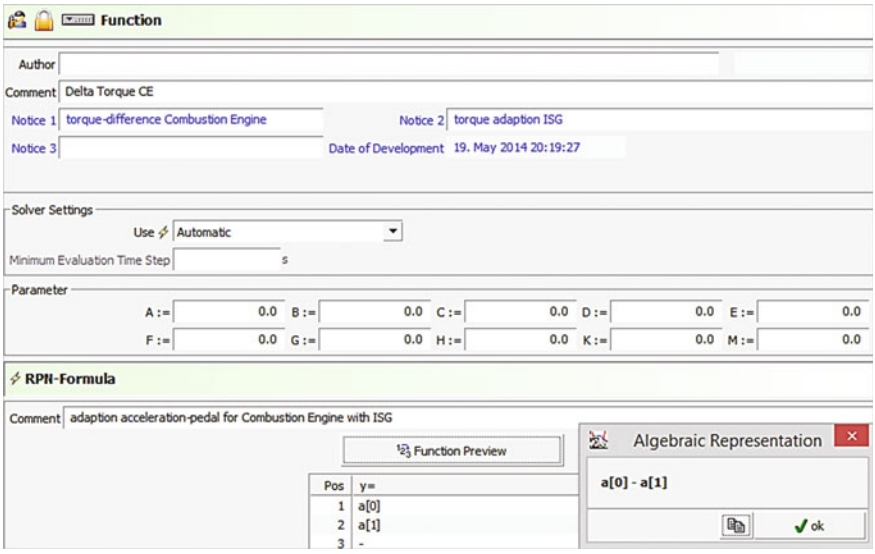


Fig. 5.35 Delta torque combustion engine input data specifications window

Table 5.27 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	Load Signal—Cockpit	–	Optional	0
a[1]	Load Signal—EMS	–	Optional	0
y[0]	Load Signal	–	Optional	0

To define component input data double click on the delta torque brake icon and enter the following data for function (Fig. 5.36), and for description of Data Bus (Table 5.28).

The **Total Torque** (22) component is a function used to calculate with user-defined functions, the summation of torque from IC Engine and ISG. To define component input data double click on the total torque icon and enter the following data for function (Fig. 5.37), and for description of Data Bus (Table 5.29).

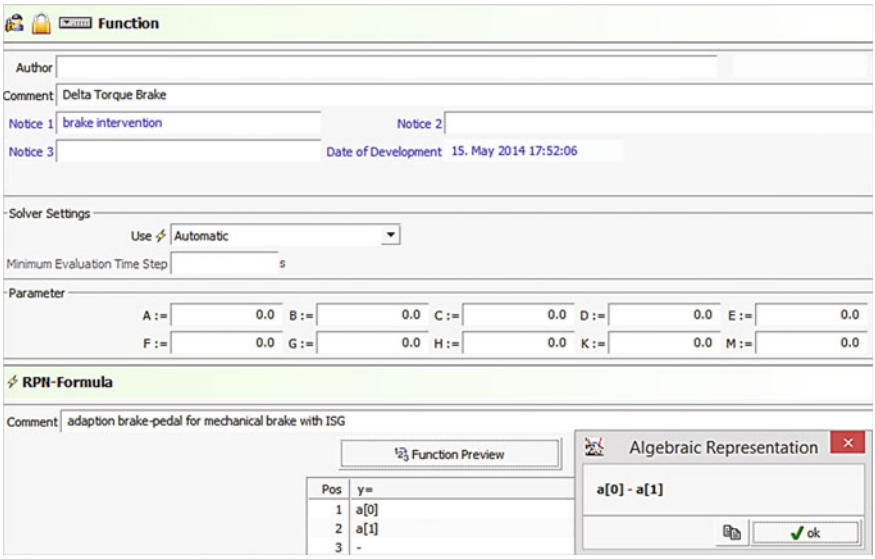


Fig. 5.36 Delta torque brake input data specifications window

Table 5.28 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	Brake Pressure—Cockpit	Pa	Optional	0
a[1]	Brake Pressure—EMS	Pa	Optional	0
y[0]	Brake Pressure	Pa	Optional	0

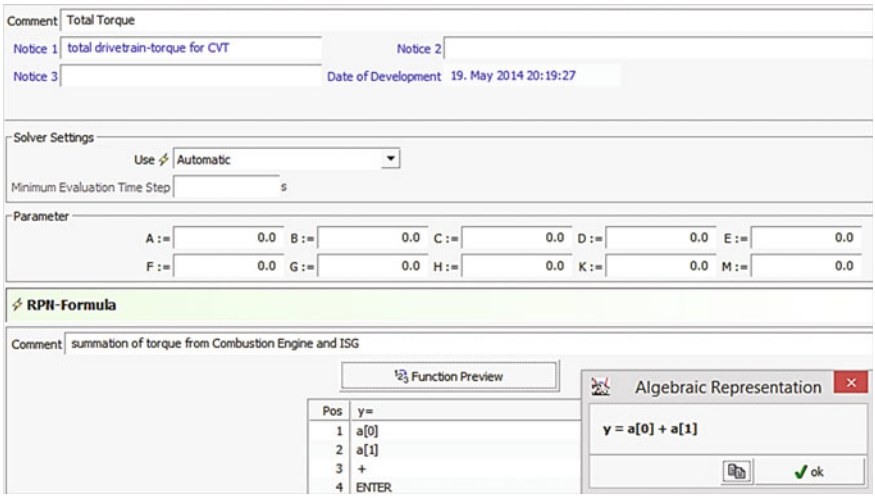


Fig. 5.37 Total torque input data specifications window

Table 5.29 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	Torque	Nm	Optional	0
a[1]	Torque behind Flywheel	Nm	Optional	0
y[0]	Torque	Nm	Optional	0

The **Monitor** component (23) can be introduced, if the calculation run must be detected.

It is possible to show some results of the calculation while the calculation is running. This is done via the online monitor. It is possible to connect up to ten input channels of the monitor to output channels of different components that are available at the AVL CRUISE—Data Bus [2].

Click on the description of Data Bus tab and open the following dialog. To select a Data Bus channel, click to access at the available list. Enter the text for the description and then click on to select the unit (Table 5.30).

Table 5.30 Description of Data Bus

Data Bus Channel	Description	Unit
Input 0	Vehicle Acceleration	m/s^2
Input 1	Vehicle Velocity	km/h
Input 2	Vehicle Distance	m
Input 3	Engine Load Signal	–
Input 4	Engine Speed	1/min

5.1.2 Hybrid Planetary Gearbox Model

This chapter describes how to create and run the simulation for a hybrid FWD model with planetary gearbox.

To place a component in the working area, click on the component group with the left mouse button, move the mouse over the required component, and then click and drag the component into the vehicle model area. Put the component with release of the mouse button on the desired place.

Place the following components in the working area: Vehicle (1), IC Engine (2), Final Drive (3), Vehicle Front Left (4), Vehicle Front Right (5), Vehicle Rear Left (6), Vehicle Rear Right (7), Front Disk Brake (8), Rear Drum Brake (9), Rear Drum Brake (10), Front Disk Brake (11), E-Machine (12), Generator (13), Differential (14), Planetary Gearbox (15), Cockpit (16), ASC (17), Battery H (18), MATLAB® DLL (19), and Monitor (20).

Arrange the components as shown in the following figure (Fig. 5.38) and connect the components as specified in the diagram [1].

All the connections in the data bus for this model are described in Table 5.31.

The **Vehicle** (1) is one of the main objects in a model. This component contains general data of the vehicle, such as nominal dimensions and weights.

To define component input data (Table 5.32) double click on the icon and select edit to open the following window (Fig. 5.39).

IC Engine (2) component contains a model for an internal combustion engine.

To define component input data (Table 5.33) double click on the icon and select edit to open the following window (Fig. 5.40).

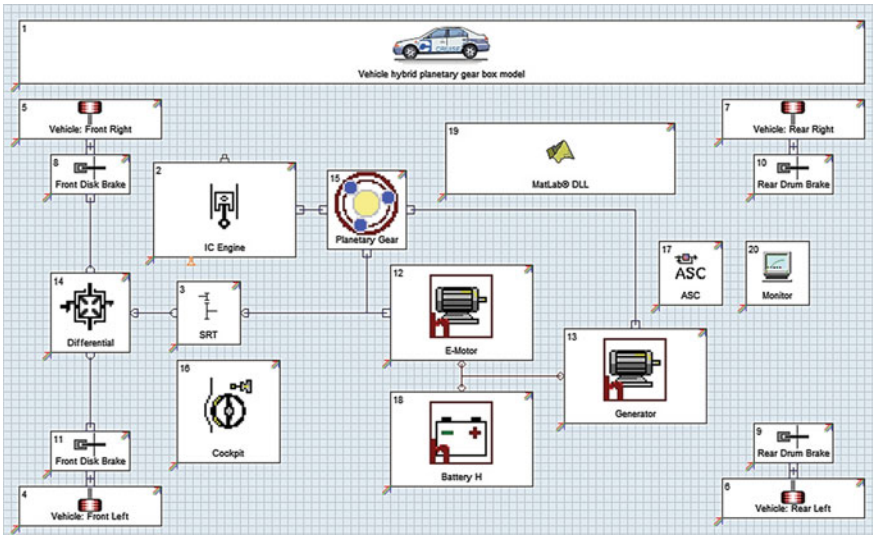


Fig. 5.38 Complete hybrid FWD model with planetary gearbox

Table 5.31 Data Bus connections

Component Requires	Input Information	Component Delivering	Output Information
ASC	**Load Signal**	Cockpit	Load Signal
	Slip Signal Front Left	Wheel Front Left	Slip Signal
	Slip Signal Front Right	Wheel Front Right	Slip Signal
Brake Front Disk	**Brake Pressure**	MATLAB® DLL	Brake Pressure
Brake Rear Drum	**Brake Pressure**	MATLAB® DLL	Brake Pressure
Brake Rear Drum	**Brake Pressure**	MATLAB® DLL	Brake Pressure
Brake Front Disk	**Brake Pressure**	MATLAB® DLL	Brake Pressure
Cockpit	**Gear Indicator**	E-Machine	Operation Control
	Operation Control 0	IC Engine	Operation Control
	Operation Control 1	E-Machine	Operation Control
	Operation Control 2	Generator	Operation Control
	Speed	Single Ratio	Input Speed
E-Machine	**Load Signal**	MATLAB® DLL	Load Signal
	Switch	MATLAB® DLL	Start Switch
Generator	**Load Signal**	MATLAB® DLL	Load Signal
	Switch	MATLAB® DLL	Start Switch
IC Engine	**Load Signal**	MATLAB® DLL	Load Signal
	Start Switch	MATLAB® DLL	Start Switch
MATLAB® DLL	Signal Acceleration	Cockpit	Load Signal
	Vehicle Velocity	Cockpit	Velocity
	Battery Status Charge	Battery H	Battery Charge
	IC Engine Torque	IC Engine	Torque Flywheel
	Generator Torque	Generator	Torque
	Generator Speed	Generator	Speed
	E-Machine Speed	E-Machine	Speed
	Brake Pressure	Cockpit	Brake Pressure
	E-Machine Torque	E-Machine	Torque
	IC Engine Speed	IC Engine	IC Engine Speed
Monitor	Vehicle Acceleration	Vehicle	Acceleration
	Vehicle Velocity	Vehicle	Velocity
	Vehicle Distance	Vehicle	Distance
	IC Engine Load Signal	IC Engine	Actual Load Signal
	IC Engine Speed	IC Engine	IC Engine Speed

To load IC Engine characteristic click on the Full Load Characteristic tab (Fig. 5.41). Select (kW) unit from the b column by pull-down menu. Add rows by clicking on and enter the following data (Table 5.34).

Table 5.32 Vehicle component input data

Name	Value	Unit
Gas Tank Volume	0.050	m^3
Distance from Hitch to Front Axle	3000.0	mm
Height of Support Point at Bench Test	100.0	mm
Wheel Base	2500.0	mm
Distance of Gravity Center empty/half/full	980.0/990.0/1000.0	mm
Height of Gravity Center empty/half/full	570.0/560.0/550.0	mm
Height of Hitch empty/half/full	400.0/390.0/380.0	mm
Tire Inflation Pressure Front Axle	2.000	bar
Tire Inflation Pressure Rear Axle	2.200	bar
Curb Weight	1200.0	kg
Gross Weight	1600.0	kg
Frontal Area	1.750	m^2
Drag Coefficient	0.300	–

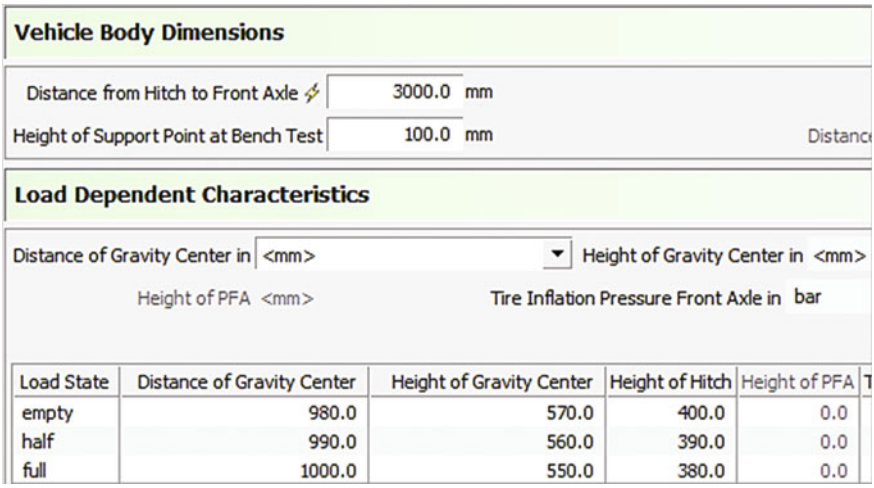


Fig. 5.39 Vehicle input data specifications window

The Motoring Curve (Fig. 5.42) will be defined similar to the Full Load Characteristic either as power dependent on the engine speeds (Table 5.35) [1].

At the Fuel Consumption Map (Fig. 5.43 and Table 5.36) the actual fuel consumption for stationary operation is listed depending on the brake mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—volume flow (l/h)) [1].

Table 5.33 IC Engine component input data

Name	Value	Unit
Engine Type	Gasoline	–
Engine Charger	Without	–
Engine Displacement	1490.0	cm^3
Engine Working Temperature	100.0	°C
Number of Cylinders	4.000	–
Number of Strokes	4.000	–
Idle Speed	900.0	1/min
Maximum Speed	4900.0	1/min
Inertia Moment	0.150	kg m^2
Response Time	0.200	s
Heating Value for Gasoline	43500.0	kJ/kg
Fuel Density	0.750	kg/l
Specific Carbon Content	0.860	–

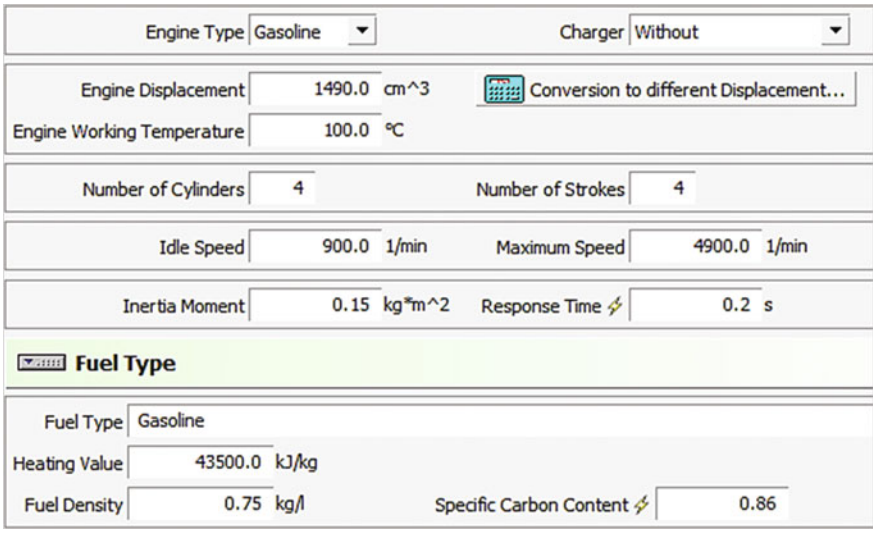


Fig. 5.40 IC Engine input data specifications window

Final Drive (3) or **Single Ratio Transmission** is a gear step with fixed ratio (Fig. 5.44). It can be used as a transmission step of the differential [2].

To define component input data double click on the final drive icon and enter the following data (Table 5.37).

The **Wheels** are: Vehicle Front Left (4), Vehicle Front Right (5), Vehicle Rear Left (6), and Vehicle Rear Right (7) with the data defined in Table 5.38 and Fig. 5.45.

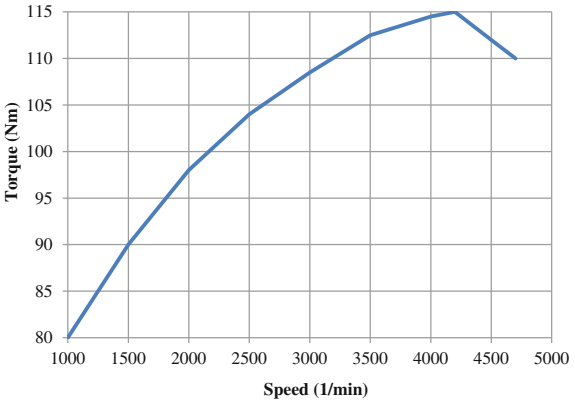


Fig. 5.41 Full Load Characteristic

Table 5.34 Full Load Characteristic data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
1000	80	3500	113
1500	90	4000	115
2000	98	4200	115
2500	104	4500	112
3000	109	4700	110

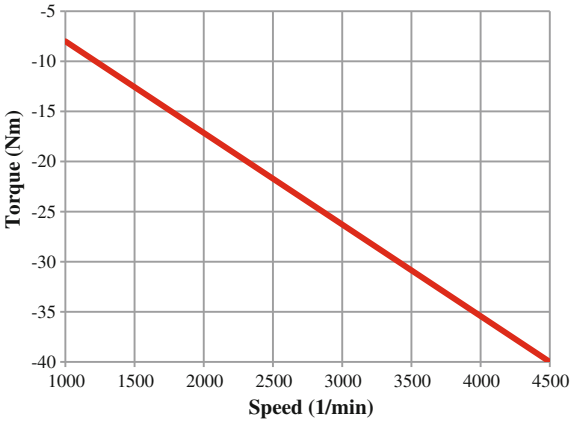


Fig. 5.42 Motoring Curve

Table 5.35 Motoring Curve data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
1000	−8.00	4500	−40.00

The **Brake** component is described by brake data and dimensions (Fig. 5.46 and Table 5.39). It is possible to define drum brakes as well as disk brakes (Front Disk Brake Right (8), Rear Drum Brake Left (9), Rear Drum Brake Right (10), and Front Disk Brake Left (11)).

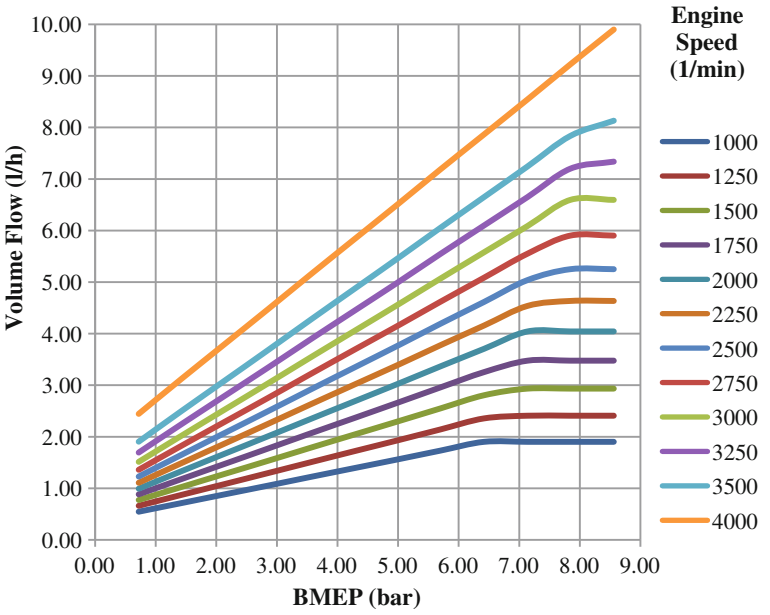


Fig. 5.43 Fuel Consumption Map

Table 5.36 Fuel Consumption Map data

(a)											
1000	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	0.54	0.71	1.05	1.22	1.39	1.73	1.90	1.90	1.90	1.90
1500	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	0.77	1.03	1.53	1.79	2.04	2.55	2.81	2.93	2.93	2.93
1750	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	0.88	1.18	1.77	2.07	2.37	2.96	3.25	3.48	3.48	3.48
2000	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	0.99	1.33	2.01	2.35	2.69	3.37	3.70	4.04	4.04	4.04
2500	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	1.23	1.65	2.50	2.92	3.34	4.19	4.62	5.04	5.25	5.25
2750	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	1.36	1.82	2.76	3.22	3.69	4.62	5.09	5.55	5.90	5.90
3000	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	1.51	2.02	3.04	3.55	4.05	5.07	5.58	6.09	6.60	6.60
3500	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	1.90	2.50	3.68	4.28	4.87	6.06	6.65	7.24	7.84	8.13
4000	(b)	0.72	1.42	2.86	3.56	4.28	5.70	6.42	7.14	7.84	8.56
	(c)	2.44	3.12	4.48	5.16	5.83	7.19	7.87	8.54	9.22	9.90

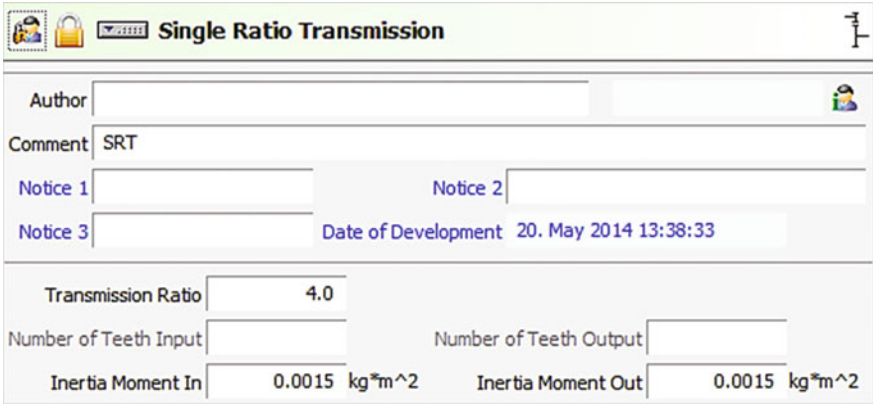


Fig. 5.44 Final Drive input data specifications window

Table 5.37 Final Drive input data

Name	Value	Unit
Transmission Ratio	4.0000	–
Inertia Moment In	0.0015	kg m^2
Inertia Moment Out	0.0015	kg m^2

Table 5.38 Wheels input data

Name	Value	Unit
Wheel Inertia Moment	0.850	kg m^2
Friction Coefficient of Tire	0.950	–
Reference Wheel Load	2500	N
Wheel Load Correction Coefficient	0.020	–
Static Rolling Radius	290.00	mm
Circumference	1822.12	mm
Dynamic Rolling Radius	295.00	mm
Circumference	1853.54	mm
Friction Coefficient of Road	1.050	–
Slip at Maximum Traction	12.50	%
Specific Traction at Infinite Slip	78.00	%
Rolling Resistance Factor	0.900	%

E-Machine (12) characteristic map for the efficiency is used to calculate the loss of power. Double click on the e-machine icon and enter the following data (Fig. 5.47 and Table 5.40).

The value of the voltage level should be entered at which the following characteristic maps of the machine have been measured (U1 = 280 V).

The maximum mechanical (power) torque (Table 5.41 and Fig. 5.48) is defined as a function of the machine speed (a—speed (1/min), b—torque (Nm)).

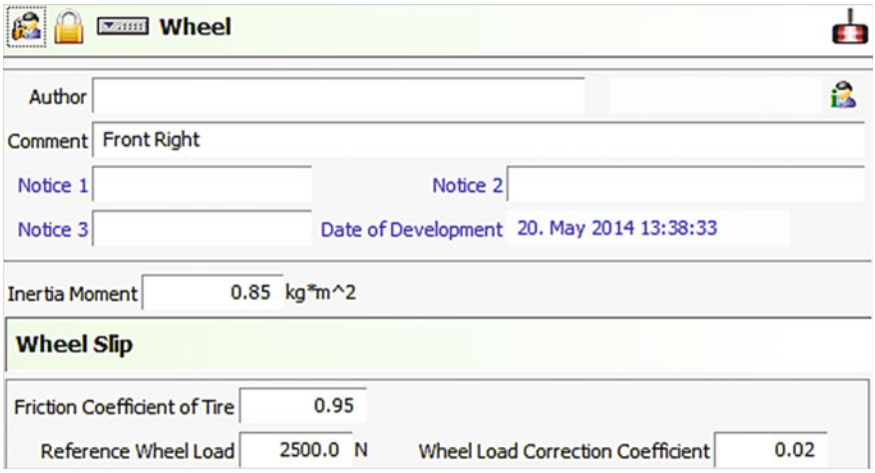


Fig. 5.45 Wheels input data specifications window

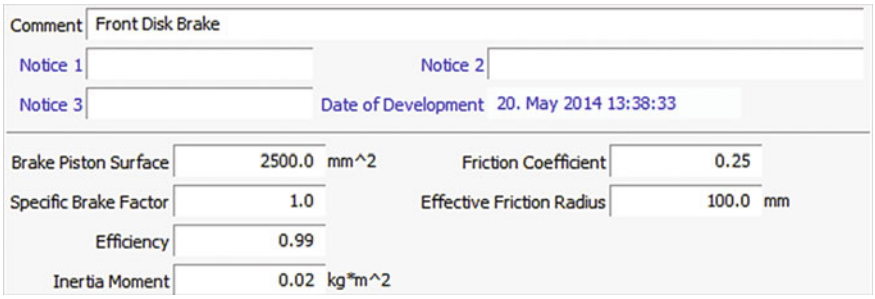


Fig. 5.46 Brake input data specifications window

Table 5.39 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	2500.0	900.0	2500.0	900.0	mm^2
Specific Factor	1.000	1.000	1.000	1.000	–
Efficiency	0.990	0.990	0.990	0.990	–
Inertia Moment	0.020	0.015	0.020	0.015	kg m^2
Friction Coefficient	0.250	0.250	0.250	0.250	–
Friction Radius	100	120	100	120	mm

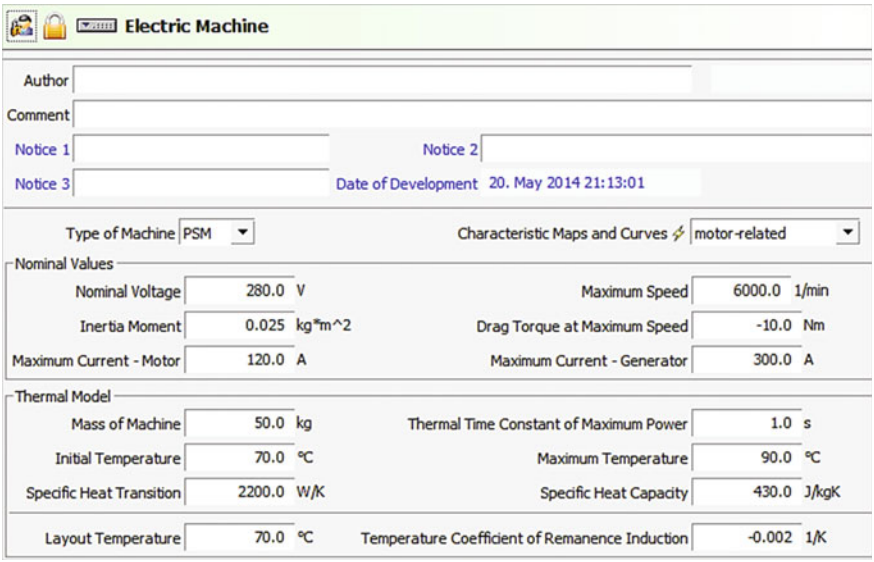


Fig. 5.47 E-Machine input data specifications window

Table 5.40 E-Machine input data

Name	Value	Unit
Type of Machine	PSM	–
Characteristic Maps and Curves	Motor-related	–
Nominal Voltage	280.0	V
Inertia Moment	0.025	kg m^2
Maximum Current—Motor	120.0	A
Mass of Machine	50.00	kg
Initial Temperature	70.00	°C
Specific Heat Transition	2200	W/K
Layout Temperature	70.00	°C
Maximum Speed	6000	1/min
Drag Torque at Maximum Speed	−10.00	Nm
Maximum Current—Generator	300.0	A
Thermal Time Constant of Max Speed	1.000	s
Maximum Temperature	90.00	°C
Specific Heat Capacity	430.0	J/kg K
Temperature Coefficient of Remanence Induction	−0.002	1/K

Table 5.41 Maximum mechanical torque data

Speed (1/min)	Torque (Nm)
0	305
500	305
1000	280
1500	192
2000	144
2500	115
3000	96
3500	82
4000	72
4500	65
6000	48

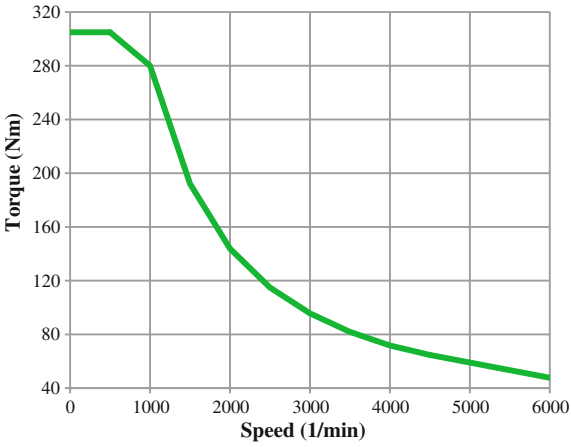


Fig. 5.48 Maximum mechanical torque

The efficiency map (Fig. 5.49 and Table 5.42) is defined dependent on a—speed (1/min), b—power (kW), and c—efficiency (%) [1].

The **Generator** (13) must supply the vehicle electrical system with a sufficient current under all operating conditions in order to ensure that the state of charge in the engine storage device is consistently maintained at an adequate level [2]. Double click on the generator icon and enter the following data (Fig. 5.50 and Table 5.43).

The maximum mechanical (power) torque (Fig. 5.51 and Table 5.44) is defined as a function of the machine speed (a—speed (1/min), b—torque (Nm)).

The alternator systems are designed to supply charge voltages of 14 V (with 28 V for heavy utility vehicles) in order to maintain an adequate charge in 12 V (or 24 V) batteries.

The current delivered by the generator results from a map dependent on the speed and the main voltage. By considering the internal resistance, the

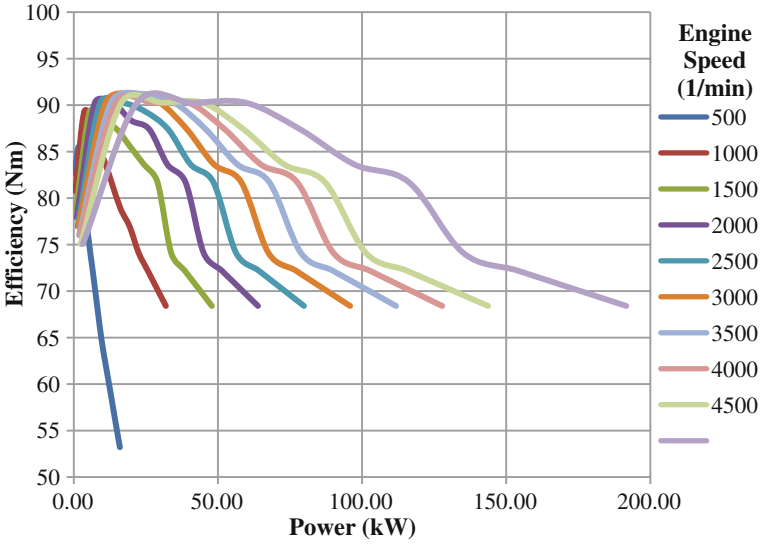


Fig. 5.49 Efficiency map

Table 5.42 Efficiency map data

(a)										
500	(b)	0.26	1.83	3.40	4.97	6.54	9.69	12.8	14.4	15.9
	(c)	82.7	85.5	80.6	76.0	72.2	64.6	58.9	56.1	53.2
1000	(b)	0.52	3.67	6.81	9.95	13.1	16.2	19.4	25.7	31.9
	(c)	80.7	89.3	86.5	84.6	81.7	78.9	76.9	72.2	68.4
1500	(b)	0.79	5.50	10.2	14.9	19.6	24.4	29.1	38.5	47.9
	(c)	78.9	89.3	88.4	87.4	85.5	83.6	81.7	72.2	68.4
2000	(b)	1.05	7.33	13.6	19.9	26.2	32.5	45.0	57.6	63.9
	(c)	77.9	90.3	90.3	88.4	87.4	83.6	74.1	70.3	68.4
2500	(b)	1.31	9.16	17.0	24.9	32.7	48.4	56.3	64.1	79.9
	(c)	76.9	90.3	90.3	89.3	87.4	81.7	74.1	72.2	68.4
3000	(b)	1.57	11.0	20.42	39.27	48.7	58.1	76.9	86.4	95.8
	(c)	76.9	90.3	91.2	87.4	83.6	81.7	72.2	70.3	68.4
3500	(b)	1.83	12.83	23.8	45.8	56.8	78.8	89.8	100	111
	(c)	76.0	90.3	91.2	87.4	83.6	74.1	72.2	70.3	68.4
4000	(b)	2.09	14.7	27.3	52.4	64.9	77.5	102	115	128
	(c)	76.0	90.2	90.3	87.4	83.6	81.7	72.2	70.3	68.4
4500	(b)	2.36	16.5	30.6	58.9	73.0	87.2	115	129	144
	(c)	75.1	90.3	90.3	87.4	83.6	81.7	72.2	70.3	68.4
6000	(b)	3.14	21.9	40.8	78.5	97.4	116	154	173	191
	(c)	75.1	90.3	90.3	87.4	83.6	81.7	72.2	70.3	68.4

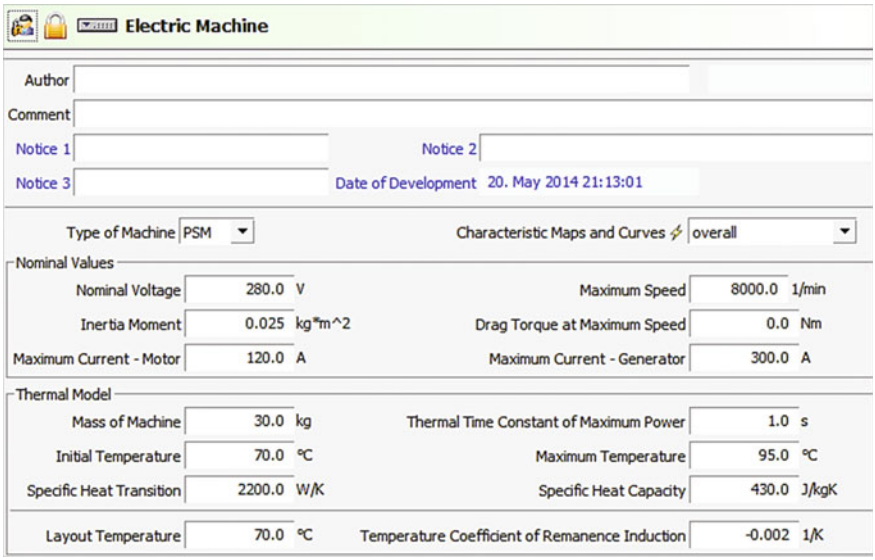


Fig. 5.50 Generator input data specifications window

Table 5.43 Generator input data

Name	Value	Unit
Nominal Voltage	280.0	V
Inertia Moment	0.025	kg m^2
Maximum Current—Motor	120.0	A
Mass of Machine	30.00	kg
Initial Temperature	70.00	°C
Specific Heat Transition	2200	W/K
Layout Temperature	70.00	°C
Maximum Speed	8000	1/min
Drag Torque at Maximum Speed	0.000	Nm
Maximum Current—Generator	300.0	A
Thermal Time Constant of Max Speed	1.000	s
Maximum Temperature	95.00	°C
Specific Heat Capacity	430.0	J/kg K
Coefficient of Remanence Induction	−0.002	1/K

instantaneous current consumption helps to acquire the torque absorbed by the generator with the corresponding moments of loss [2].

The efficiency map (Fig. 5.52 and Table 5.45) is defined dependent on a—speed (1/min), b—power (kW) and efficiency (%).

The **Differential** (14) is a particular type of simple planetary gear train that has the property that the angular velocity of its carrier is the average of the angular

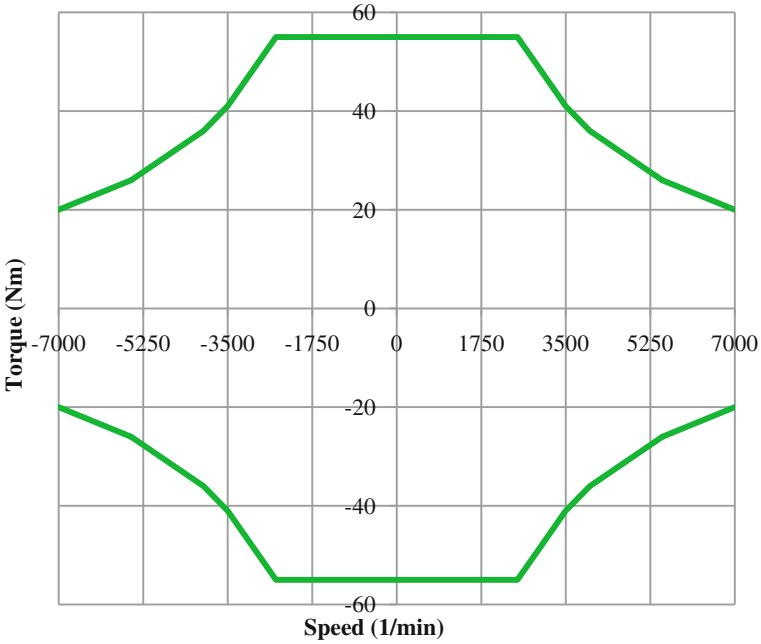


Fig. 5.51 Maximum mechanical torque

Table 5.44 Maximum mechanical torque data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
0	55	0	−55	−7000	−20	−7000	20
500	55	500	−55	−5500	−26	−5500	26
1000	55	1000	−55	−4000	−36	−4000	36
1500	55	1500	−55	−3500	−41	−3500	41
2000	55	2000	−55	−3000	−48	−3000	48
2500	55	2500	−55	−2500	−55	−2500	55
3000	48	3000	−48	−2000	−55	−2000	55
3500	41	3500	−41	−1500	−55	−1500	55
4000	36	4000	−36	−1000	−55	−1000	55
5500	26	5500	−26	−500	−55	−500	55
7000	20	7000	−20	0	−55	0	55

velocities of its sun and annular gears. To define component input data double click on the differential icon and enter the following data (Fig. 5.53 and Table 5.46).

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component (Fig. 5.54—E-Machine, Fig. 5.55—IC Engine).

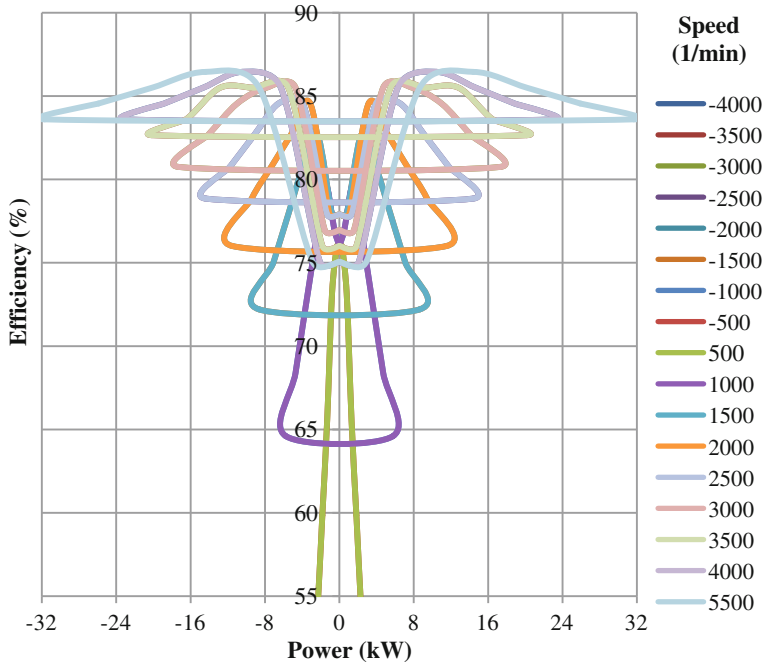


Fig. 5.52 Efficiency map

The **Cockpit** (16) links the driver and the vehicle. In this component connections are only made via the Data Bus. The pedal positions are transferred into corresponding indicators via the pedal characteristics (Table 5.47).

To define the input data click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)) and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data for all (Fig. 5.56).

The **ASC Anti-Slip Control** (17) checks the force transmission factor of all connected wheels (Fig. 5.57). The Anti-Slip Control is only active when a model is calculated quasi-stationary in combination with special drive train configurations and does not require data entry [2].

If the Anti-Slip Control should be used for calculations in simulation mode, this switch can be activated. In this case the parameters for the PID controller can be set (proportional—1 (−), differential—0 (s), and integral parameter—1 (1/s)).

The **Battery H** (18) component is used to simulate hybrid vehicles (Fig. 5.58). Double click on the battery H icon and enter the following data (Table 5.48).

The idle voltage—charge (b) is a function of the State of Charge SOC (a) (Fig. 5.59 and Table 5.49), and the idle voltage—discharge (b) is a function of the SOC (a) (Fig. 5.60 and Table 5.50).

Table 5.45 Efficiency map data

(a)											
−4000	(b)	2	6	11	19	23	−23	−19	−11	−6	−2
	(c)	75	85	87	84	83	83	84	87	85	75
−3500	(b)	2	6	9	16	20	−20	−16	−9	−6	−2
	(c)	76	85	86	83	82	82	83	86	85	76
−3000	(b)	2	5	8	14	17	−17	−14	−8	−5	−2
	(c)	77	86	85	82	80	80	82	85	86	77
−2500	(b)	1	4	7	11	14	−14	−11	−7	−4	−1
	(c)	78	85	84	81	79	79	81	84	85	78
−2000	(b)	1	3	7	9	11	−11	−9	−7	−3	−1
	(c)	77	84	81	78	76	76	78	81	84	77
−1500	(b)	1	2	4	6	9	−9	−6	−4	−2	−1
	(c)	78	82	80	77	72	72	77	80	82	78
−1000	(b)	1	2	3	4	6	−6	−4	−3	−2	−1
	(c)	77	80	76	72	64	64	72	76	80	77
−500	(b)	0	1	2	2	3	−3	−2	−2	−1	0
	(c)	76	65	59	54	49	49	54	59	65	76
500	(b)	0	1	2	2	3	−3	−2	2	−1	0
	(c)	76	66	60	54	50	50	54	60	66	76
1000	(b)	1	2	3	4	5	−5	−4	−3	−2	−1
	(c)	77	80	76	72	68	68	72	76	80	77
1500	(b)	1	2	4	7	8	−8	−7	−4	−2	−1
	(c)	78	83	81	75	72	72	75	81	83	78
2000	(b)	1	3	5	9	11	−11	−9	−5	−3	−1
	(c)	78	85	83	81	76	76	81	83	85	78
2500	(b)	1	4	7	11	14	−14	−11	−7	−4	−1
	(c)	77	85	84	80	78	78	80	84	85	77
3000	(b)	2	5	8	14	17	−17	−14	−8	−5	−2
	(c)	76	86	85	82	80	80	82	85	86	76
3500	(b)	5	9	13	16	20	−20	−16	−13	−9	−5
	(c)	85	86	86	83	82	82	83	86	86	85
4000	(b)	6	10	15	19	23	−23	−19	−15	−10	−6
	(c)	86	87	85	84	83	83	84	85	87	86
5500	(b)	9	15	20	24	31	−31	−24	−20	−15	−9
	(c)	85	87	86	84	83	83	84	86	87	85

MATLAB® DLL (19) interface allows to integrate controllers or also mechanical elements, such as special drives, which have been created using MATLAB®/Simulink™ into the computational model of AVL CRUISE (Fig. 5.61).

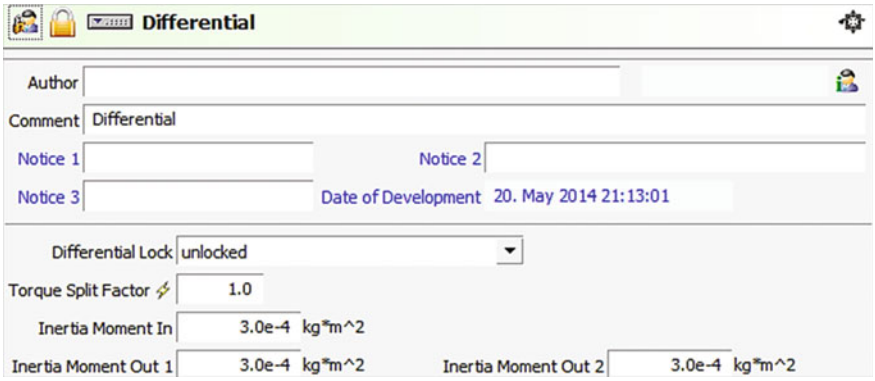


Fig. 5.53 Differential input data specifications window

Table 5.46 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.000	–
Inertia Moment In	3.0e−4	kg m^2
Inertia Moment Out1	3.0e−4	kg m^2
Inertia Moment Out2	3.0e−4	kg m^2

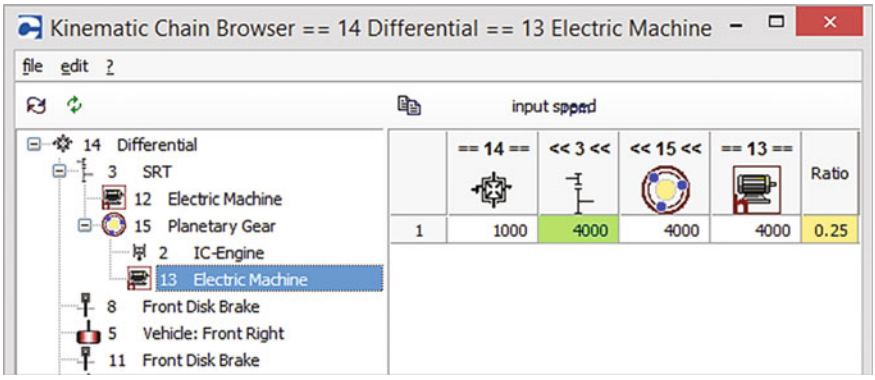


Fig. 5.54 Kinematic Chain Browser E-Machine

The compiled DLL file will be loaded from folder: project/version/userdata/_MatLab_Controller.dll. The input values are transferred to the MATLAB® function [2]. The results are received and input to the output channels (Table 5.51).

The **Monitor** (20) can be introduced, if the calculation run must be detected (Fig. 5.62). It is possible to show some results of the calculation while the calculation is running. This is done via the online monitor. It is possible to connect up to

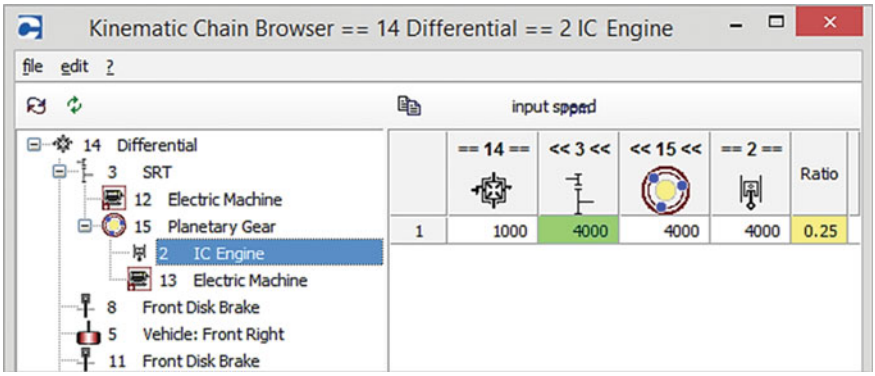


Fig. 5.55 Kinematic Chain Browser IC Engine

Table 5.47 Cockpit input data

Name	Value	Unit
Shift Mode	Automatic	–
Number of Gears Forward	1.00	–
Number of Gears Back	0.00	–
Maximum Brake Force	100.0	N
Brake Light Switch Threshold	1.0.0	%
Number of Retarder Steps	0.00	–

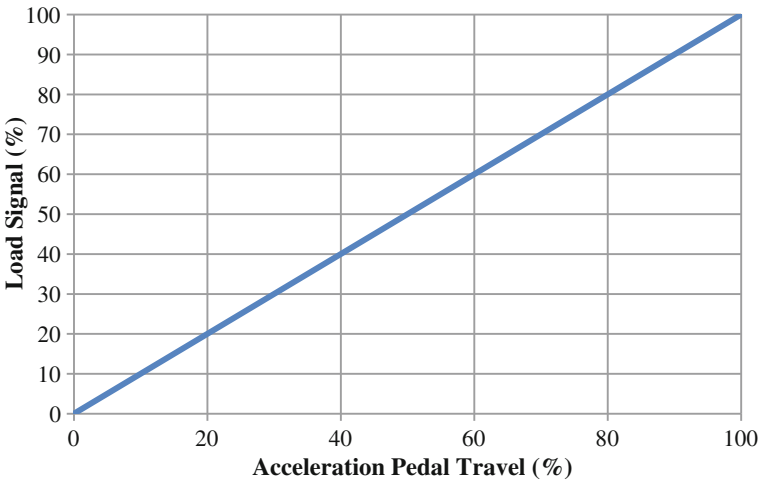


Fig. 5.56 Pedal characteristic

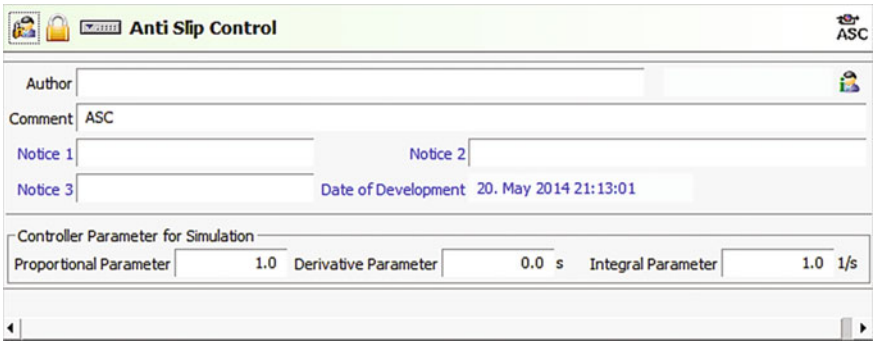


Fig. 5.57 ASC Anti-Slip Control input data specifications window

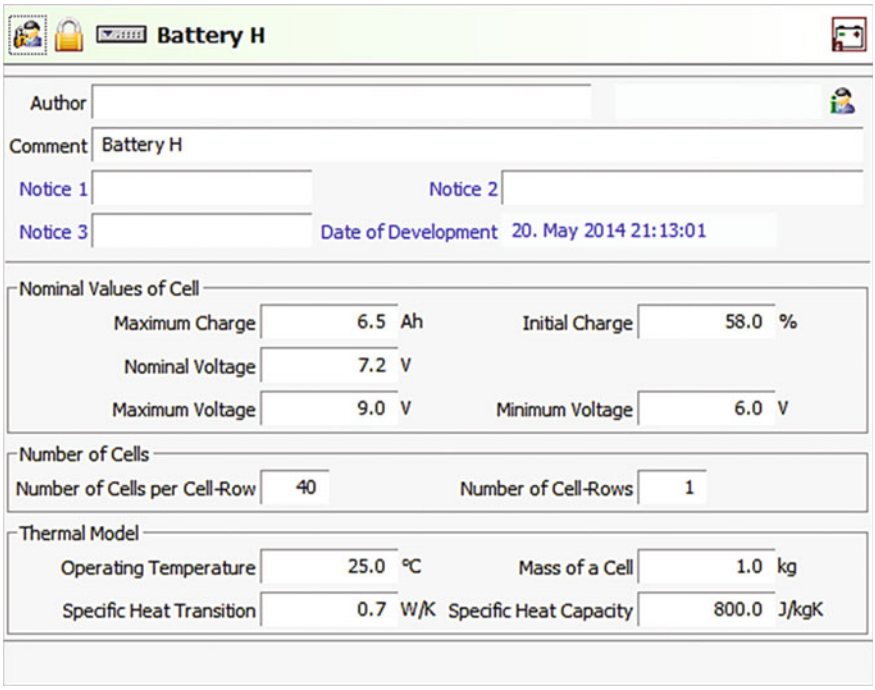


Fig. 5.58 Battery H input data specifications window

ten input channels of the monitor to output channels of different components that are available at the AVL CRUISE—Data Bus [2].

Click on the description of Data Bus tab and open the following dialog. To select a Data Bus channel, click to access at the available list. Enter the text for the description and then click on to select the unit (Table 5.52).

Table 5.48 Battery H input data

Name	Value	Unit
Maximum Charge	6.5	Ah
Nominal Voltage	7.2	V
Maximum Voltage	9.0	V
Initial Charge	65	%
Minimum Voltage	6	V
Number of Cells per Cell-Row	40	–
Number of Cell-Row	1	–
Operating Temperature	25	°C
Mass of a Cell	1	kg
Specific Heat Transition	0.7	W/K
Specific Heat Capacity	800	J/kg K
Internal Resistance	0.02	Ω

Fig. 5.59 Idle voltage charge

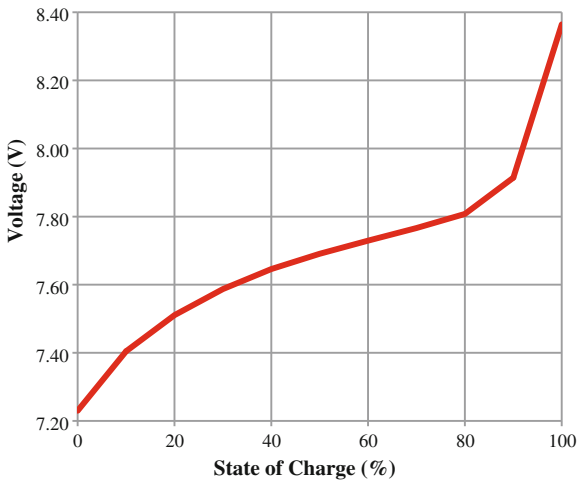


Table 5.49 Idle voltage—charge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	7.23	60	7.73
10	7.40	70	7.77
20	7.51	80	7.81
30	7.59	90	7.91
40	7.65	100	8.36
50	7.69	–	–

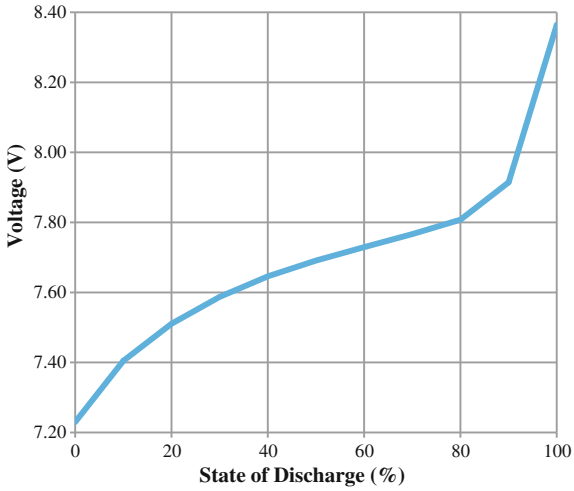


Fig. 5.60 Idle voltage discharge

Table 5.50 Idle voltage—discharge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	7.23	60	7.73
10	7.40	70	7.77
20	7.51	80	7.81
30	7.59	90	7.91
40	7.65	100	8.36
50	7.69	–	–

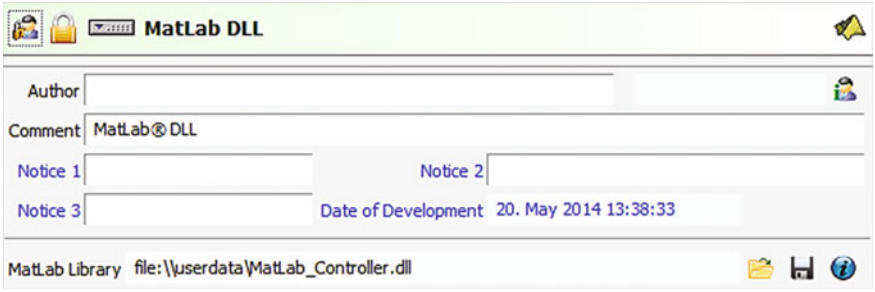


Fig. 5.61 MATLAB® DLL

Table 5.51 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
Inport 0	Load Signal (Acceleration)	–	Optional	0
Inport 1	Vehicle Velocity	m/s	Optional	0
Inport 2	Battery State of Charge (SOC)	As	Optional	0
Inport 3	IC Engine Torque	Nm	Optional	0
Inport 4	Generator Torque	Nm	Optional	0
Inport 5	Generator Speed	rad/s	Optional	0
Inport 6	Electric Motor Speed	rad/s	Optional	0
Inport 7	Brake Pressure	bar	Optional	0
Inport 8	Electric Motor Torque	Nm	Optional	0
Inport 9	IC Engine Speed	rad/s	Optional	0
Inport 10	Electric Motor Current	A	Optional	0
Inport 11	Electric Motor Voltage	V	Optional	0
Inport 12	Alternator Current	A	Optional	0
Inport 13	Alternator Voltage	V	Optional	0
Inport 14	Battery Current	A	Optional	0
Inport 0	Load Signal (Acceleration)	–	Optional	0
Inport 1	Vehicle Velocity	m/s	Optional	0
Inport 2	Battery State of Charge (SOC)	As	Optional	0
Inport 3	IC Engine Torque	Nm	Optional	0
Inport 4	Generator Torque	Nm	Optional	0
Inport 5	Generator Speed	rad/s	Optional	0
Inport 6	Electric Motor Speed	rad/s	Optional	0
Inport 7	Brake Pressure	bar	Optional	0
Inport 0	Load Signal (Acceleration)	–	Optional	0

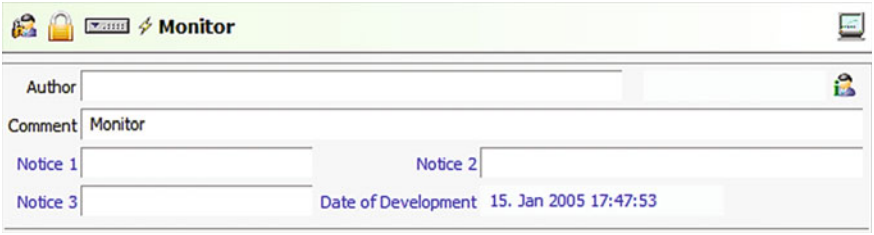


Fig. 5.62 Monitor

Table 5.52 Description of Data Bus

Data Bus Channel	Description	Unit
Input 0	Vehicle Acceleration	m/s^2
Input 1	Vehicle Velocity	km/h
Input 2	Vehicle Distance	m
Input 3	Engine Load Signal	–
Input 4	Engine Speed	1/min

5.2 Run Simulation

5.2.1 Result Manager

To run a simulation for each model, there are five different options for calculation [2]:

- Single Calculation is a regular calculation with the input data supplied in the components. Output of result defines which components result will be written and available in the Result Manager.
- Matrix Calculation is used for multiple calculations and to evaluate the effect of varying the values of input parameters on vehicle performance, consumption, and emissions. The results can be viewed for each varied calculation.
- Component Variation is used for multiple calculations and the calculation consists of sub-calculations in which components are replaced by components of the same type. The results can be viewed in the Result Manager.
- System Variation is used for multiple calculations from a list of all the model's systems. The results can be viewed similar to Component Variation.
- Batch Calculation is used for calculations of series of different projects, either Single Calculation, Matrix Calculation with DoE option and Component Variation with DoE option.

To run the calculation in the Desk Area click on Calculation Center or click on AVL blue button in the upper right corner (Fig. 5.63). Click on to "Start Calculation" button to run the simulation.

After the simulations are complete click on the Result Manager in the Navigation Frame (Fig. 5.64) and expand the task of which the results should be viewed. The selected object is shown in the right section of the window.

Project information can be viewed in the main window by selecting info in the tree structure or by double clicking info in the right window. The window shows general information: project name, author, vehicle model, drivetrain model, date and state (regarding errors), then the tree structure of the folder with defined Calculation Tasks (different status for run or not run is shown using blue/gray color). The picture of the Vehicle Model is also displayed.

One output file is produced for each component in the Vehicle Model and each Calculation Task. Data for diagrams are extracted from these files and are shown as Energy Flow Graphics, presentation diagrams for belonging task and standard diagrams for used components.

In the tree structure of the Result Manager all defined Calculation Task folders are shown separately for each task. Those folders with results are shown in color; tasks which are not run are gray. Files of the each Calculation Task are located inside the respective folder. In Result Manager, all components are listed where results have been written in pages mode or data sources mode (Fig. 5.65).

The result output for components is selected with output in the properties window of the respective component. Select as defined in module for output of

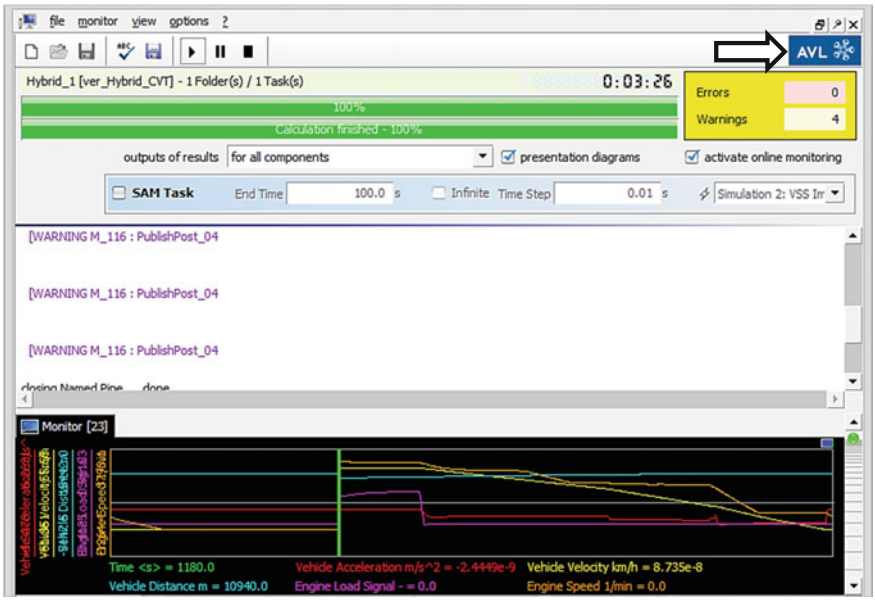


Fig. 5.63 Start calculation

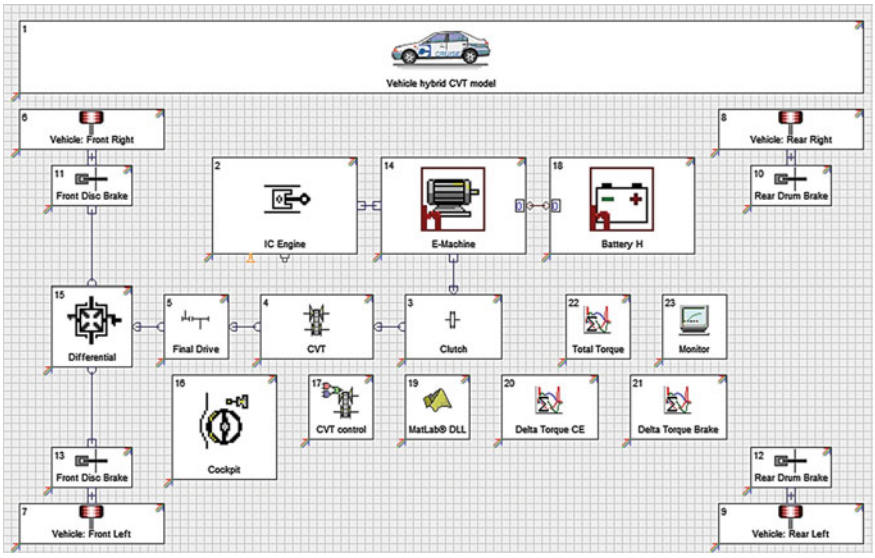


Fig. 5.64 Result Manager window

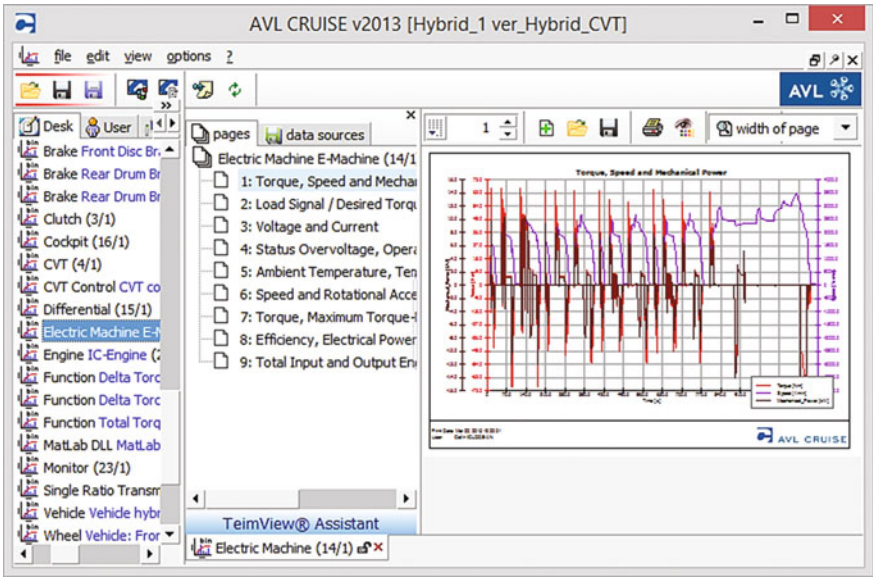


Fig. 5.65 Result Manager pages mode

results in the folder of the corresponding calculation task. There are two types of result outputs available with the Result Manager: standard diagrams and presentation diagrams.

Standard diagrams (Fig. 5.66) are created separately for each component and only contain results of the individual component and represent time histories of the single components.

They have a predefined representation page, which can only be changed in some parts. Standard diagrams are opened by selecting the respective calculation task in the tree structure of Result Manager and then selecting the corresponding component.

The pages mode sidebar is divided into a list of predefined standard diagram pages for the respective component and TeimView Assistant with a tree structure of components with all available curves and the current parameter for current diagram of respective component with the list of all used curves. TeimView has two mode tabs: pages and data sources. Pages are used to view results as curves in standard diagram and data sources in tables as numerical data for the respective component for analyzing and extracting [2].

The data sources mode sidebar (Fig. 5.67) has a tree structure where the data source, data file, and table are shown. In data source view is a list of all curve data that can be shown.

Energy Flow Graphics feature can be selected in the Result Manager (Fig. 5.68). An animation shows the flow between the drivetrain components over time of the

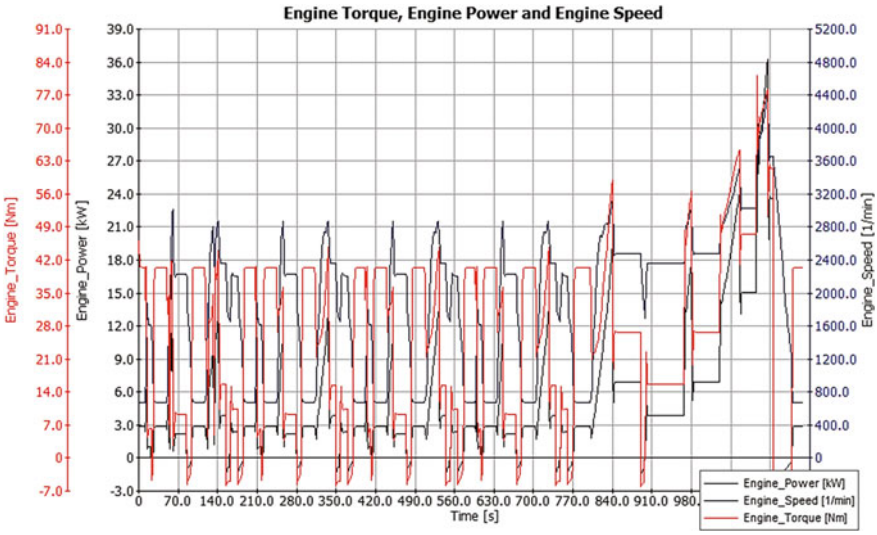


Fig. 5.66 Standard diagrams

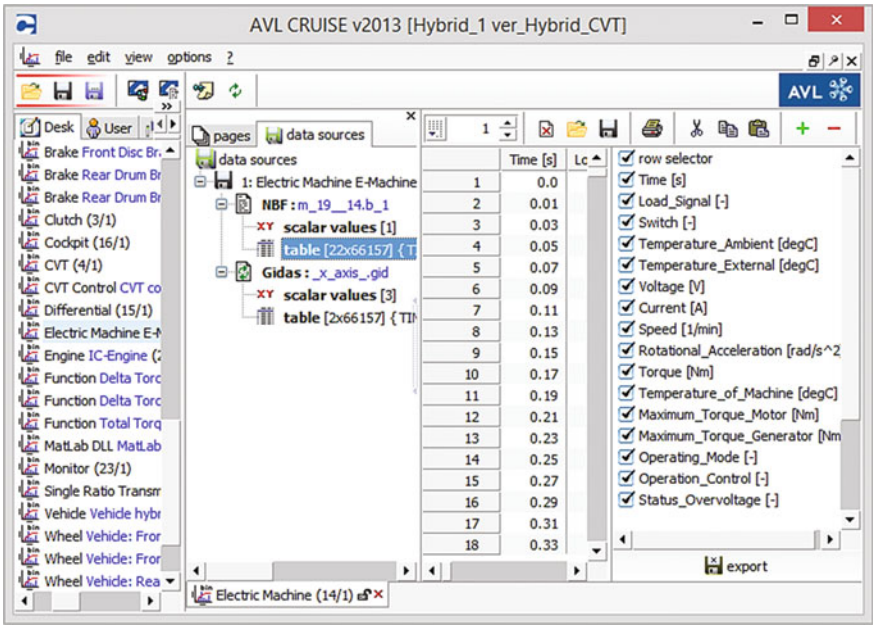


Fig. 5.67 Result Manager data sources mode

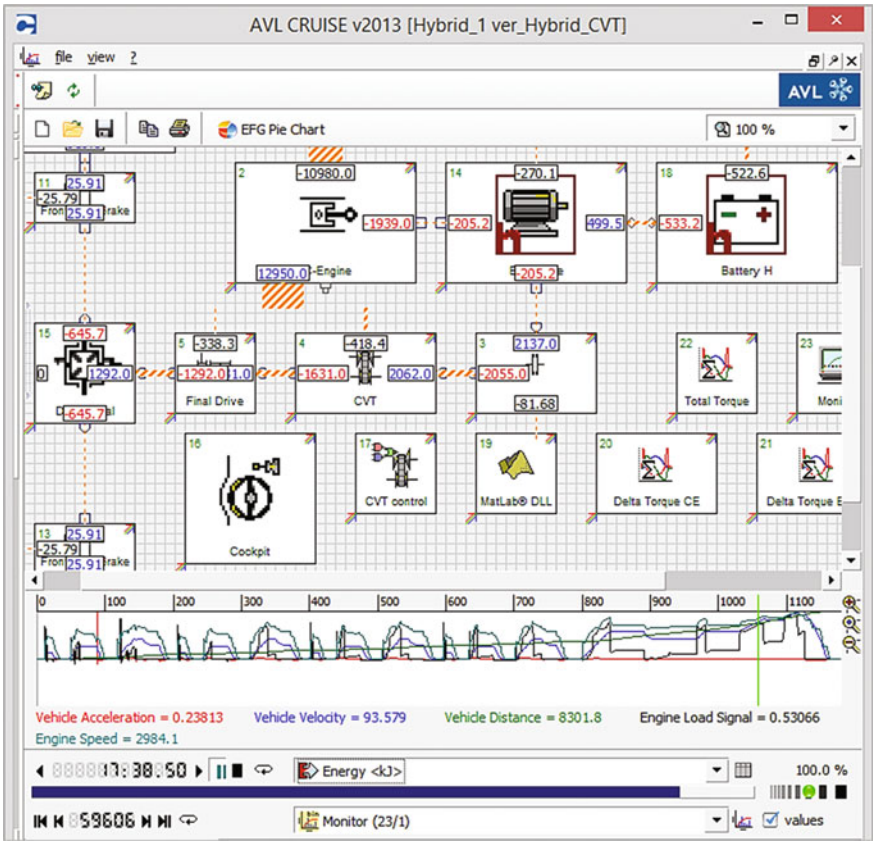


Fig. 5.68 Energy Flow Graphics

following parameters: Current (A), Energy Stored (kJ), Energy (kJ), Power (kW), Speed (1/min), Velocity (km/h), Torque (Nm), Force (N), Voltage (V).

The animation can be controlled by appropriate switches (play, pause, stepwise, stop, repeat, velocity). A time bar, showing the actual simulation time, can be moved to a certain time step with the mouse.

Below the Energy Flow Graphics a monitor is shown which displays the result curves of selected components. With a zoom option, the horizontal direction can be scaled so that long cycles can also be viewed properly.

In addition to the graphical representation, the associated values can also be displayed in the monitor as well as in the drivetrain flow graphics.

The values of the Energy Flow Graphics can also be displayed in a pie chart.

Clicking the button EFG pie chart opens an area where the segments can be added or removed with the buttons "+" and "−".

The association between a segment and a component parameter can be done by marking the segment in the segment list and then doing a left mouse click on a

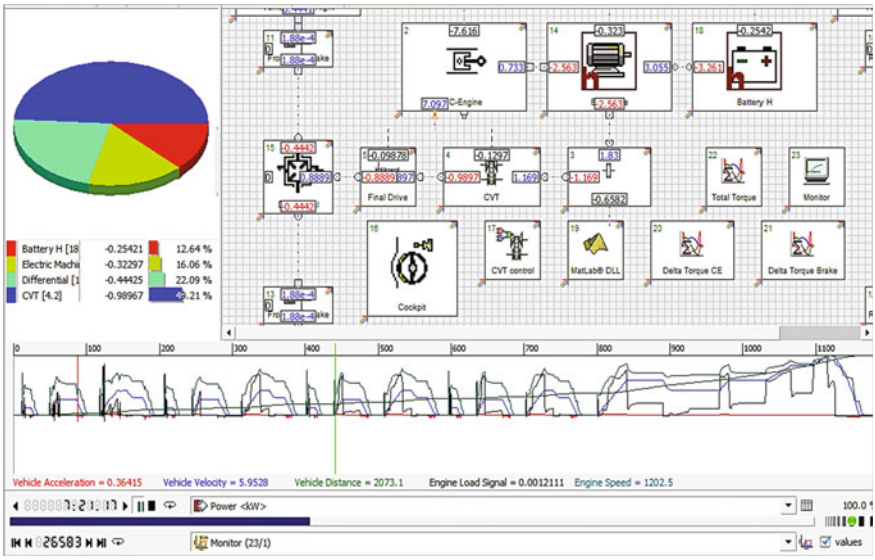


Fig. 5.69 EFG pie chart

so-called connector of the component (Fig. 5.69). Several connectors can be chosen for one segment. In that case, the segment represents the sum of all associated values. The segment list consists of the absolute segment values as well as of the values in terms of percentages [2].

The task of the mode trimap is to construct a 3D surface and describe it by iso-lines. The input data which is data of 3D points is projected into the x-y-surface and are triangulated (in 2D). The iso-lines are created by an intersection list (Fig. 5.70).

5.2.2 Standard Diagrams

To evaluate the fuel economy characteristics of the IC Engine motored bus was running a typical NEDC cycle (Fig. 5.71). The total distance of this cycle is 10.931 m, the total time is 1180 s, idle standing time is 267 s, average speed including stops is 33.35 km/h, average driving speed excluding stops is 43.10 km/h, average acceleration is 0.506 m/s^2, and maximum acceleration is 1.042 m/s^2.

The statistical percentages of IC Engine operating region are found in condensation map and are show in Fig. 5.72. Driving time distribution in consumption map is show in Fig. 5.73.

The fuel consumption of all engines can be evaluated overall, and at idle speed, acceleration, constant ad deceleration as shown in Fig. 5.74, the electrical power, maximum power out and maximum power input are shown in Fig. 5.75 and for the

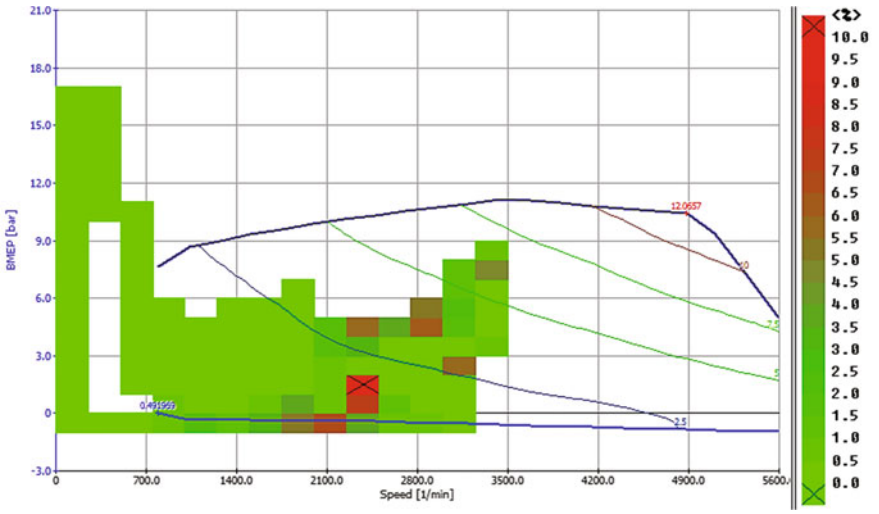


Fig. 5.70 Trimap diagram

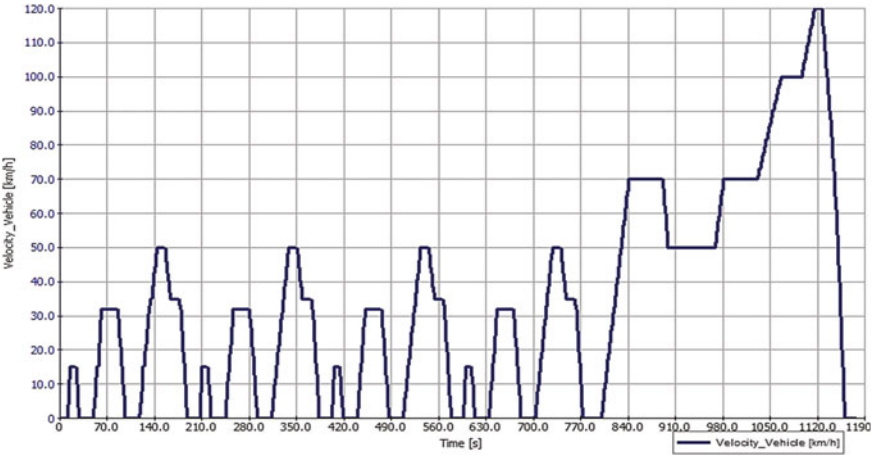


Fig. 5.71 NEDC typical cycle

hybrid version also the charge, voltage, current, and State of Charge (SOC) are important to monitor (Fig. 5.76).

During the test cycle, the electrical power and power loss are also monitored (Fig. 5.77), and in Fig. 5.78 the total output and total input energy variation can be seen. The clutch and brake travel are shown in Fig. 5.79, and in Fig. 5.80 the brake pedal travel is correlated to the power of all brakes, also for the braking, in

CHARACTERISTIC DATA		
Curb Weight	<kg>:	1300.0
Vehicle Mass	<kg>:	1300.0
Frontal Area	<m2>:	2.000
Drag Coefficient	<->:	0.300
Displacement	<l>:	1.460
Number of Cylinders	<->:	4
Number of Strokes	<->:	4
stat. Roll. Radius	<mm>:	290.0
dyn. Roll. Radius	<mm>:	310.0
Calculation Mode: Simulation 2		
Slip	: Off	

Speed [1/min]	Torque [Nm]	Abund. [%]	Abund. [s]
150.28	2.74	22.7	267.9
1875.0	-0.14	11.52	135.97
2375.0	1.05	10.21	120.51
2356.07	15.57	8.95	105.61
2125.0	-4.34	8.41	99.21
1220.04	-2.15	8.11	95.74
1625.0	-2.62	6.61	78.01
2848.18	57.0	5.61	66.2
2271.91	46.67	5.48	64.61
822.26	0.81	4.93	58.18
3138.59	35.93	3.42	40.39
2741.55	-0.39	2.19	25.9
3298.36	86.86	1.68	19.78
389.14	135.56	0.17	2.0

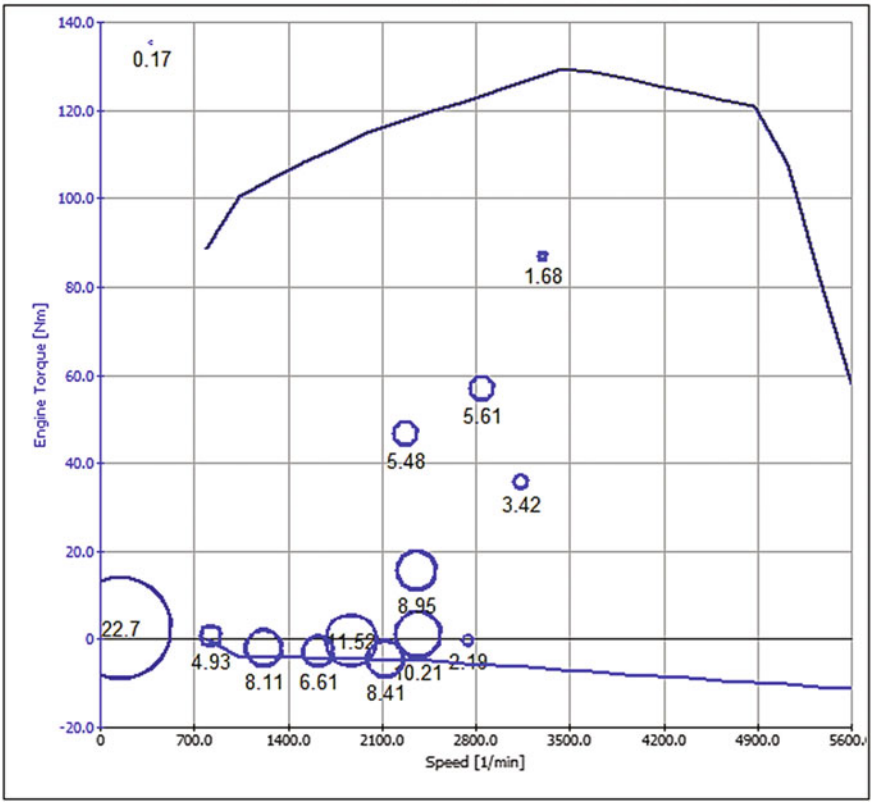


Fig. 5.72 Statistical percentages of engine operating region

Fig. 5.81, the braking torque and braking power are shown with the vehicle speed. The raw emissions are shown in Fig. 5.82, while the speed input and output are shown in Fig. 5.83.

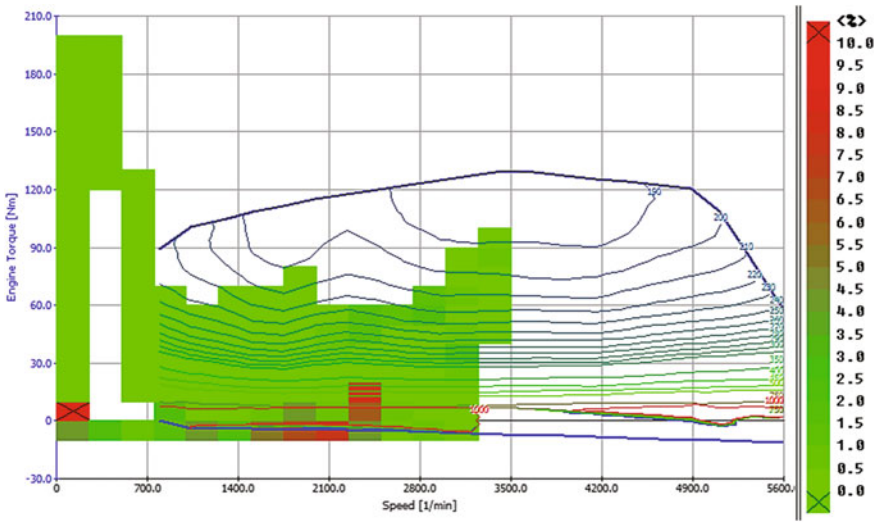


Fig. 5.73 Driving time distribution in consumption map

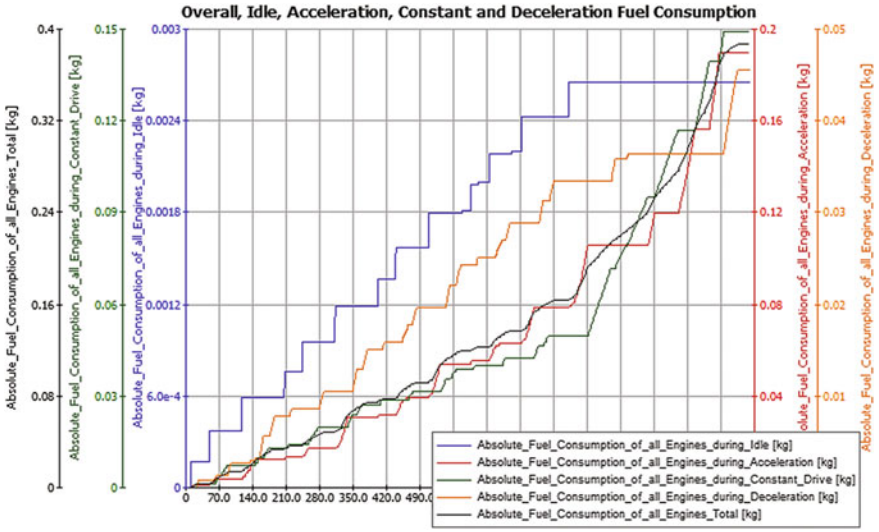


Fig. 5.74 All engine fuel consumptions

Rotational acceleration input and output (Fig. 5.84), clutch torque and maximum torque (Fig. 5.85); acceleration, velocity, and distance (Fig. 5.86), load signal, brake pressure, and clutch release (Fig. 5.87); operation control and speed (Fig. 5.88); desired gear and current gear (Fig. 5.89) are all automatically generated graphs.

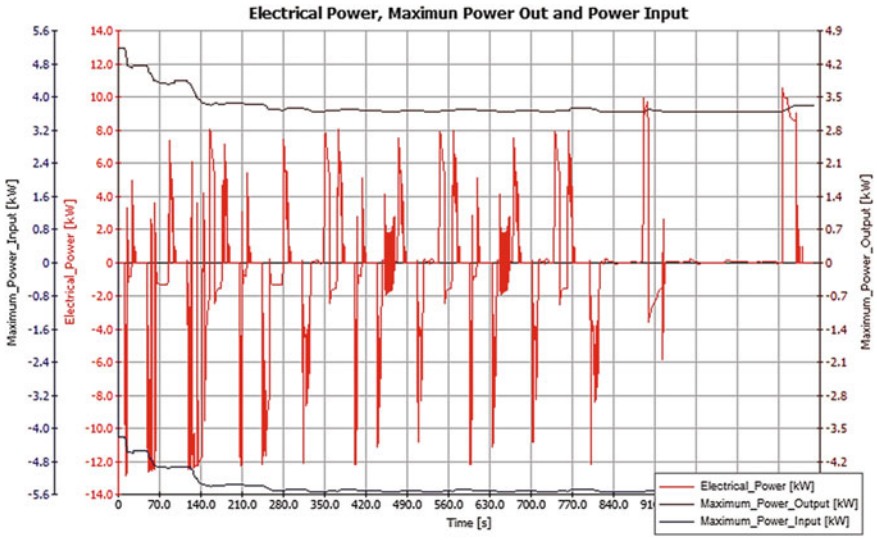


Fig. 5.75 Electrical power, maximum power output, and maximum power input evaluation

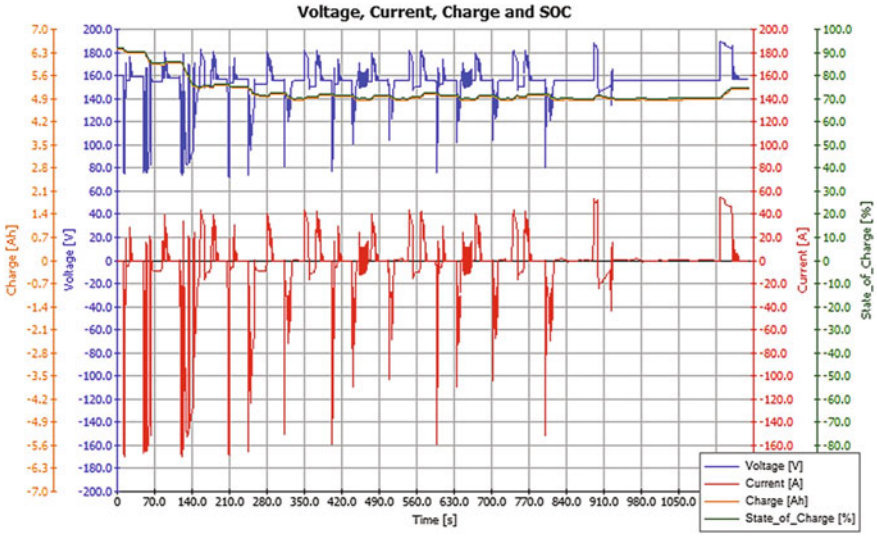


Fig. 5.76 Charge, voltage, current, and State of Charge (SOC) monitoring

The real time, current gear, and velocity are shown in Fig. 5.90; speed input and output in Fig. 5.91, torque input, output, and loss in Fig. 5.92, torque loss and efficiency in Fig. 5.93, desired transmission ratio and transmission ratio in Fig. 5.94, input and output speeds in Fig. 5.95, torque inputs and outputs in Fig. 5.96, torque,

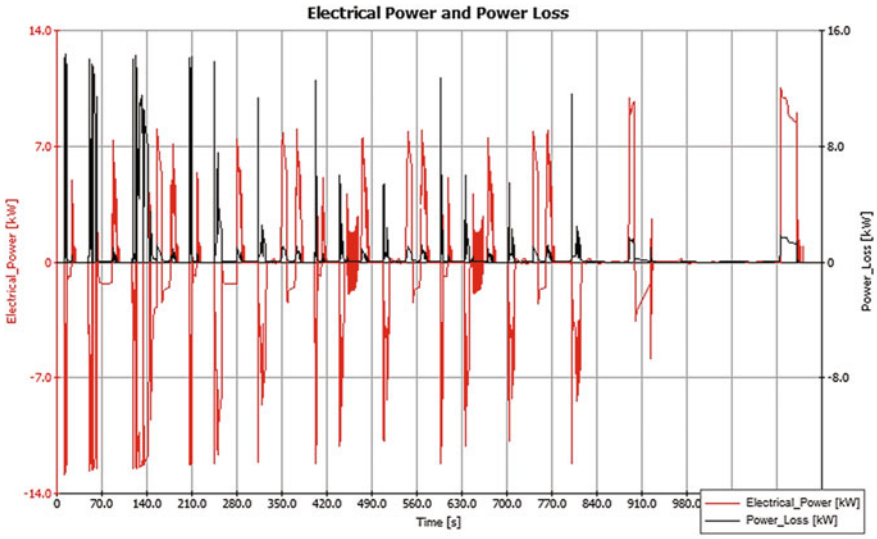


Fig. 5.77 Electrical power and power loss

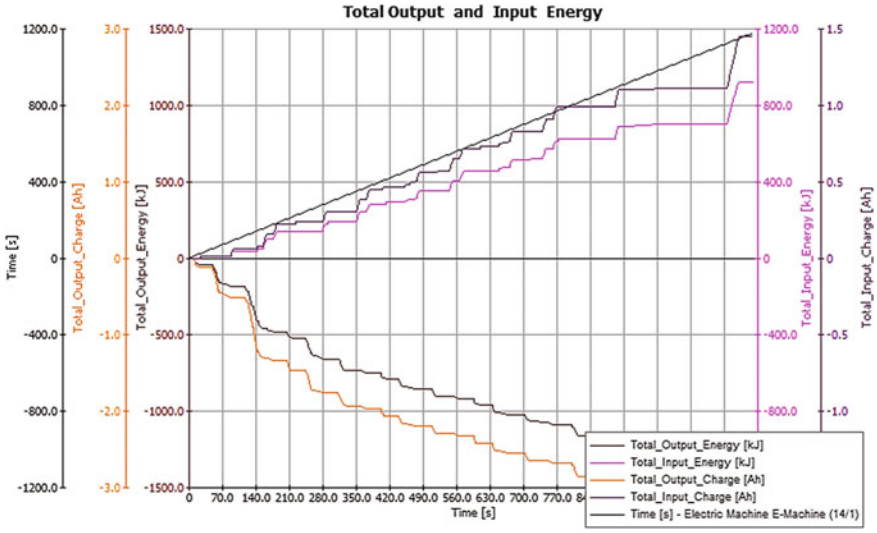


Fig. 5.78 Total output and total input energy variation

speed, and mechanical power in Fig. 5.97, load signal, desired torque, and start switch in Fig. 5.98.

From the electric motor, the voltage and current (Fig. 5.99) can be extracted, but also: status overvoltage, operating mode, and operation control (Fig. 5.100), speed

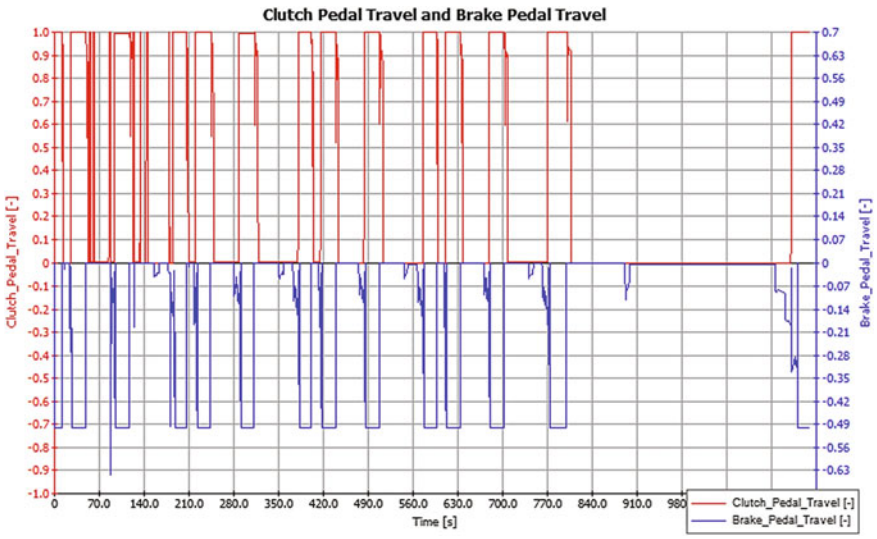


Fig. 5.79 Clutch and brake travel

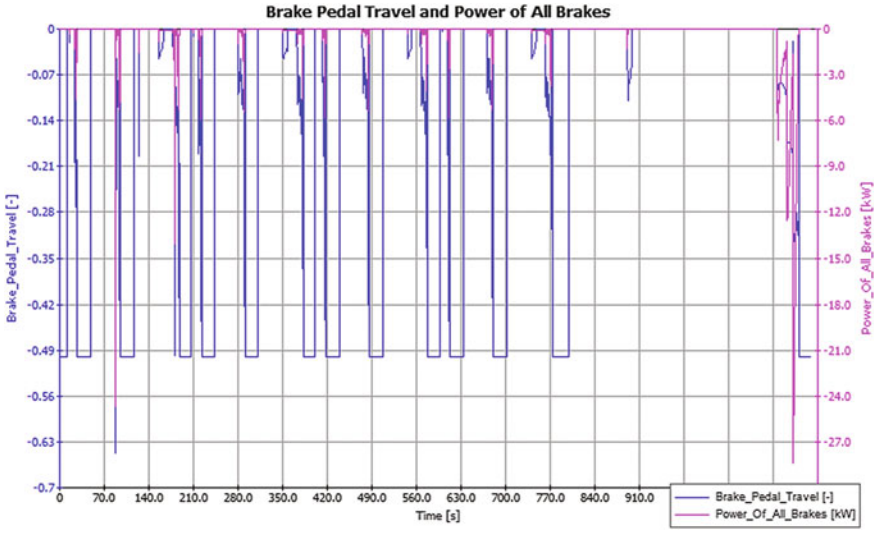


Fig. 5.80 Brake pedal travel and power of all brakes

and rotational acceleration (Fig. 5.101), torque, maximum torque generator, and maximum torque motor (Fig. 5.102), efficiency, electrical power, and power loss (Fig. 5.103), total input and output energy (Fig. 5.104), engine torque, power, and speed (Fig. 5.105), engine torque and mean effective pressure (Fig. 5.106), engine

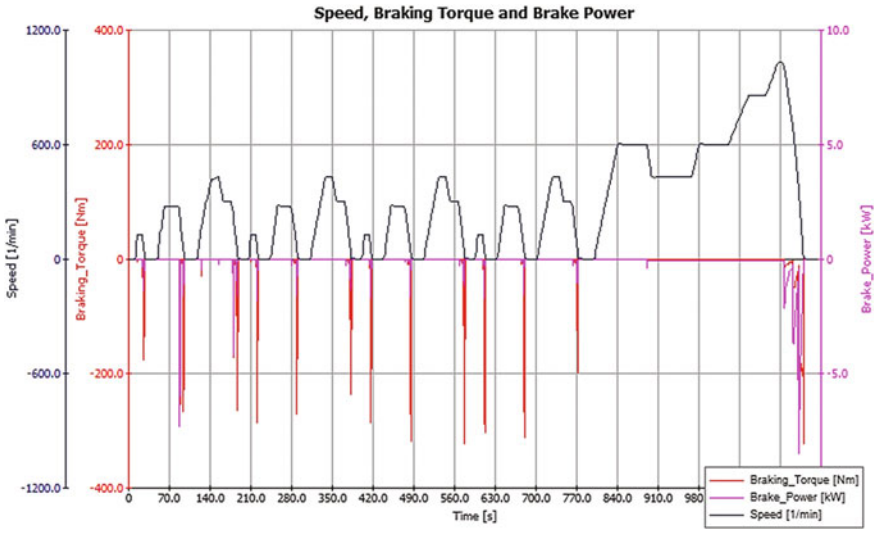


Fig. 5.81 Braking torque, braking power, and speed

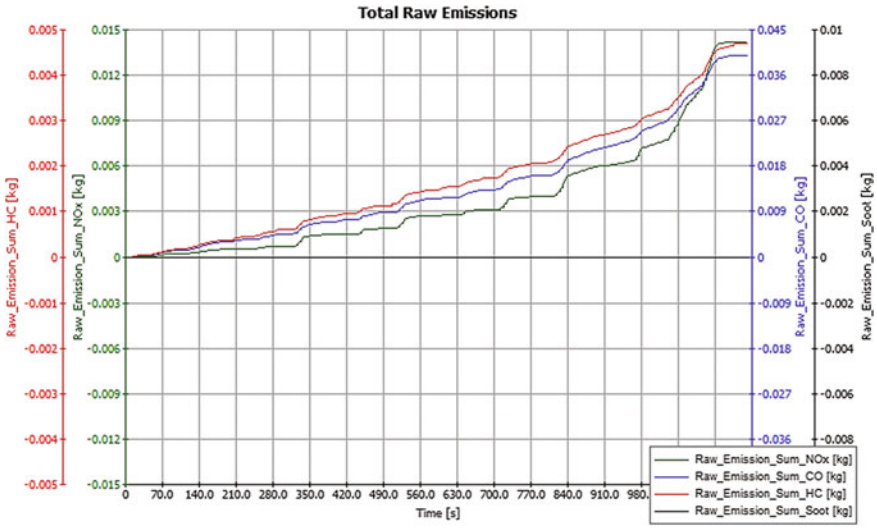


Fig. 5.82 Raw NO_x, CO, HC, and Soot emissions

activation, mean effective pressure, and fuel consumption (Fig. 5.107), engine temperature and load signal (Fig. 5.108), HC, NO_x, CO, and Soot emissions (Fig. 5.109), engine rotational acceleration (Fig. 5.110), cold start factor and fuel consumption (Fig. 5.111), power correction factor and engine torque (Fig. 5.112), load signal, operator control and start switch (Fig. 5.113).

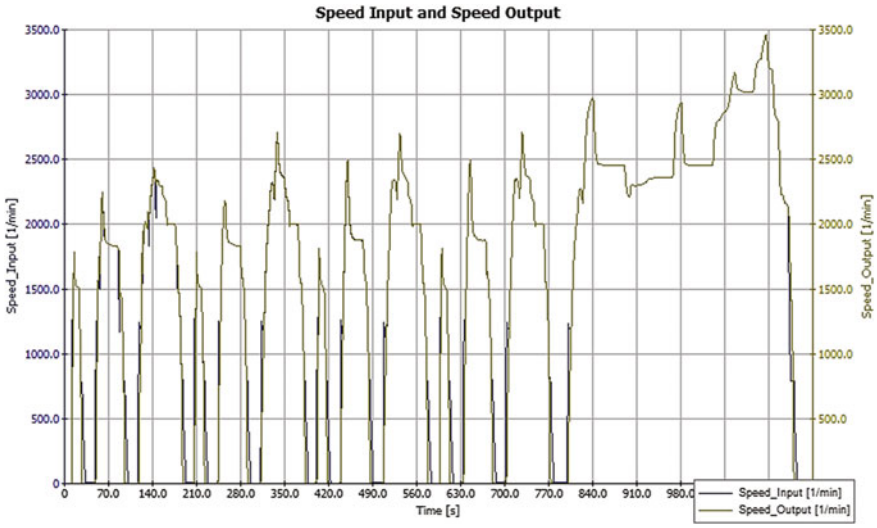


Fig. 5.83 Speed input and output

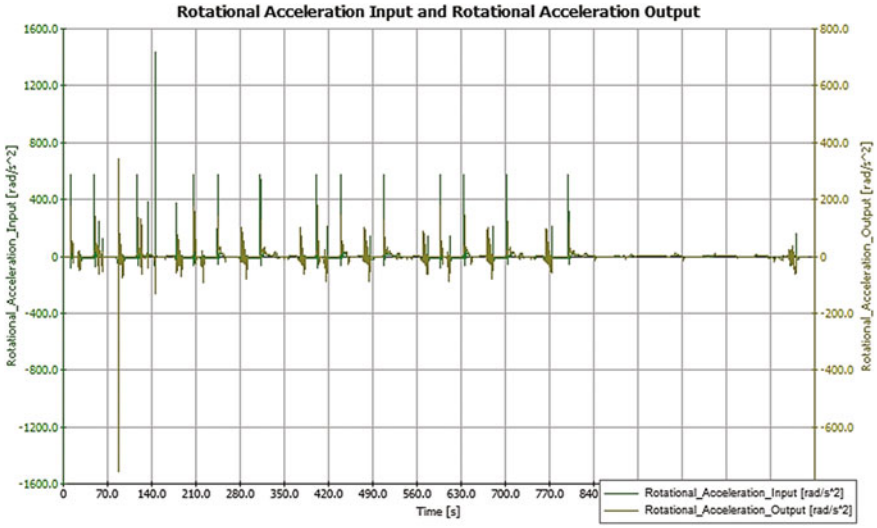


Fig. 5.84 Rotational acceleration input and output

For all inputs and outputs, a specific graph can be made: brake pressure—cockpit (Fig. 5.114), brake pressure—EMS (Fig. 5.115), brake pressure—output (Fig. 5.116), load signal—cockpit (Fig. 5.117), load signal—EMS (Fig. 5.118), load signal—output (Fig. 5.119), torque—input (Fig. 5.120), torque behind flywheel (Fig. 5.121), velocity (Fig. 5.122), battery charge (Fig. 5.123).

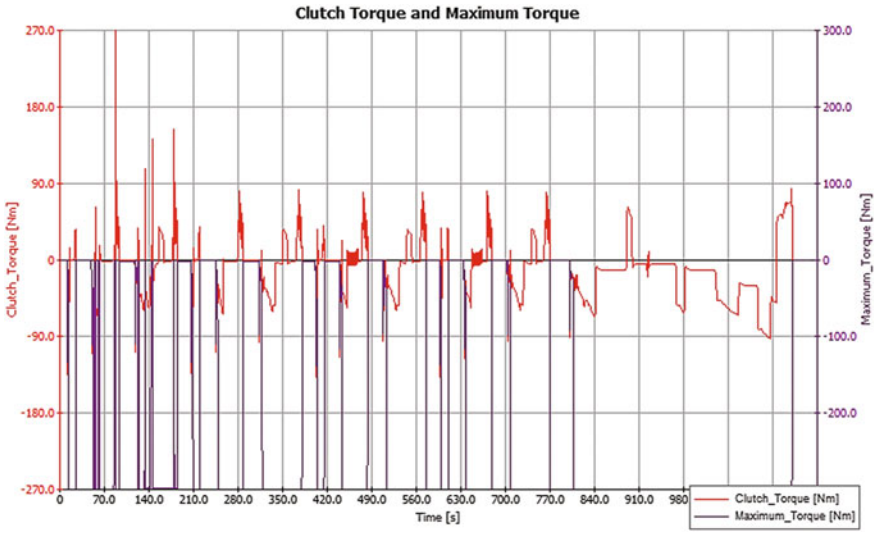


Fig. 5.85 Clutch torque and maximum torque

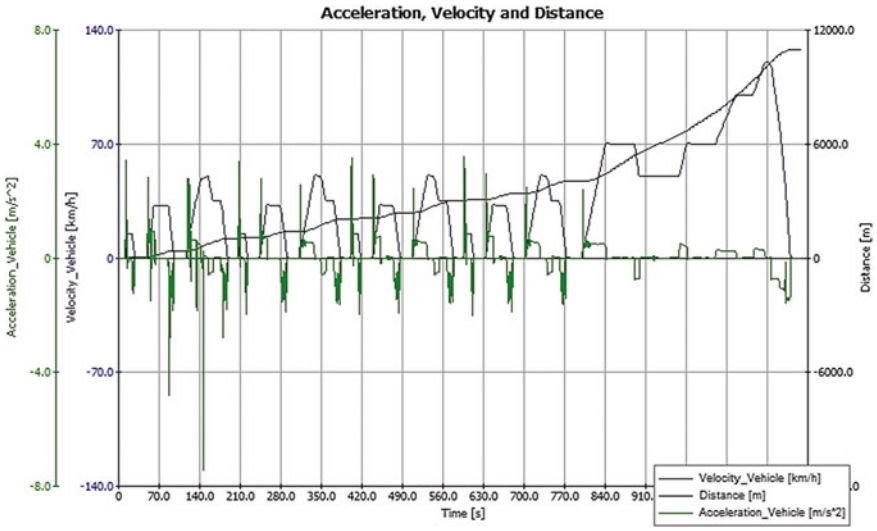


Fig. 5.86 Acceleration, velocity, and distance

Further inputs and outputs can generate the following graphs: current transmission ratio (Fig. 5.124), actual clutch release (Fig. 5.125), current—input (Fig. 5.126), load signal—EMS—output (Fig. 5.127), load signal—output (Fig. 5.128), vehicle distance—input (Fig. 5.129), engine load signal—input (Fig. 5.130), speed input and output (Fig. 5.131), efficiency and torque loss

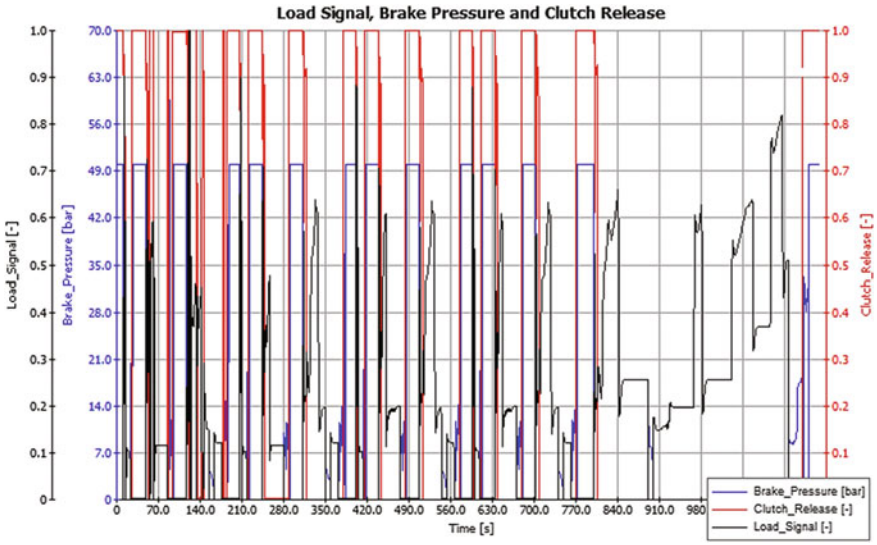


Fig. 5.87 Load signal, brake pressure, and clutch release

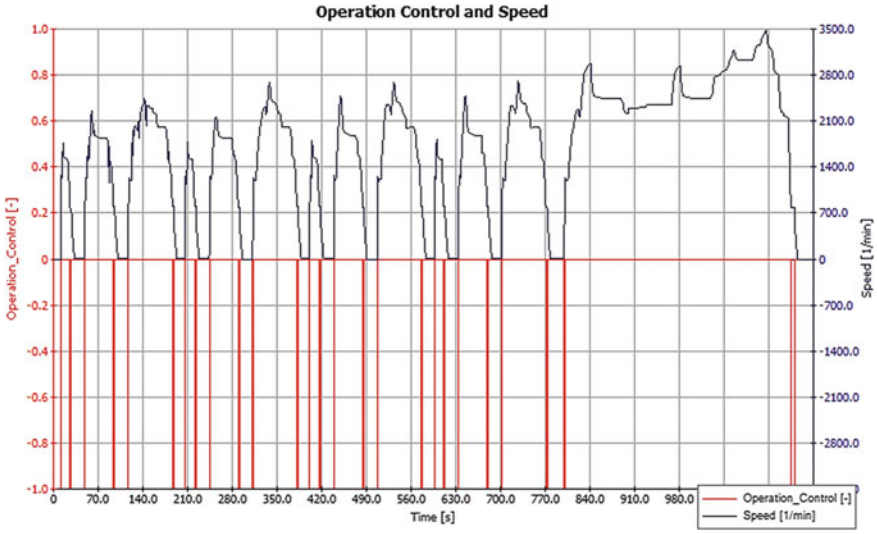


Fig. 5.88 Operation control and speed

(Fig. 5.132), air resistance force, resistance force, and traction force (Fig. 5.133), wheel loads front (Fig. 5.134), wheel loads rear (Fig. 5.135), axle loads (Fig. 5.136), speed and rotational acceleration (Fig. 5.137), friction coefficient and friction coefficient exploit (Fig. 5.138), longitudinal force and slip (Fig. 5.139),

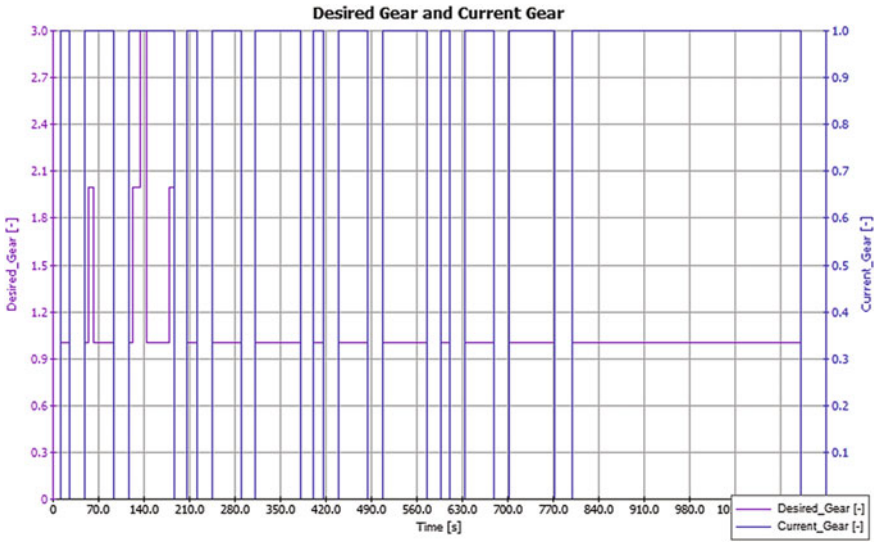


Fig. 5.89 Desired gear and current gear

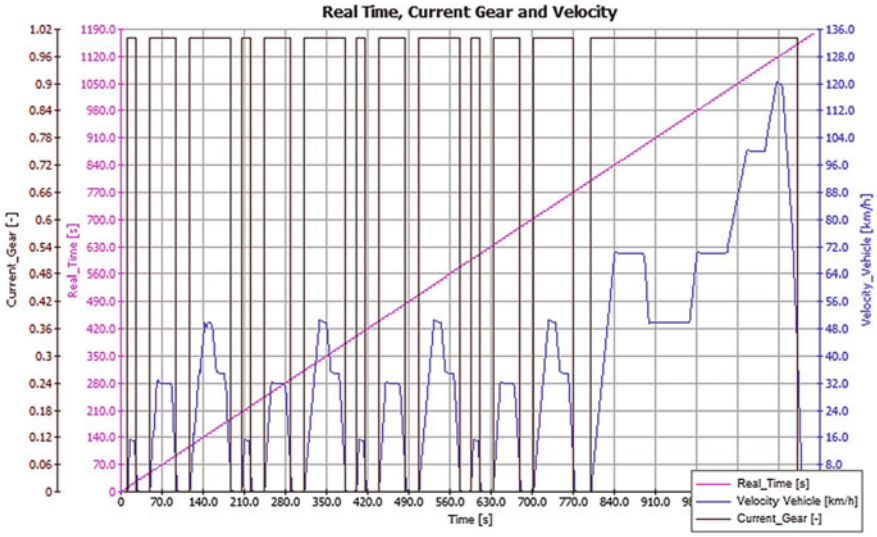


Fig. 5.90 The real time, current gear, and velocity

clutch pedal travel and acceleration pedal travel (Fig. 5.140), brake pedal travel and acceleration pedal travel (Fig. 5.141), distance, velocity, and acceleration of the vehicle (Fig. 5.142), electrical consumption and fuel consumption (Fig. 5.143), load signal and vehicle acceleration (Fig. 5.144).

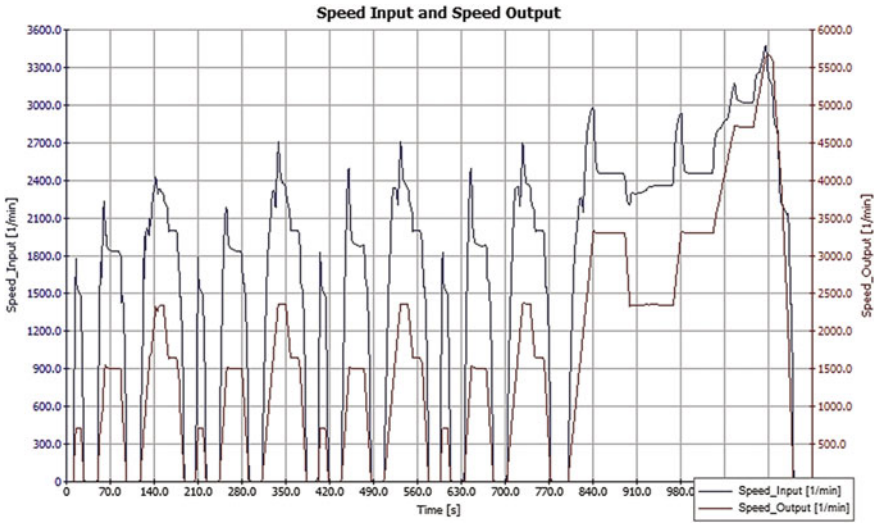


Fig. 5.91 Speed input and output

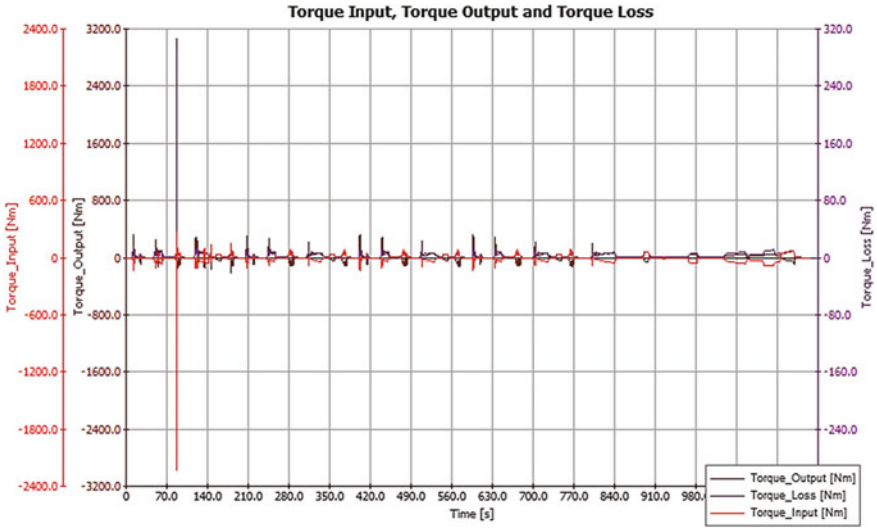


Fig. 5.92 Torque input, output, and loss

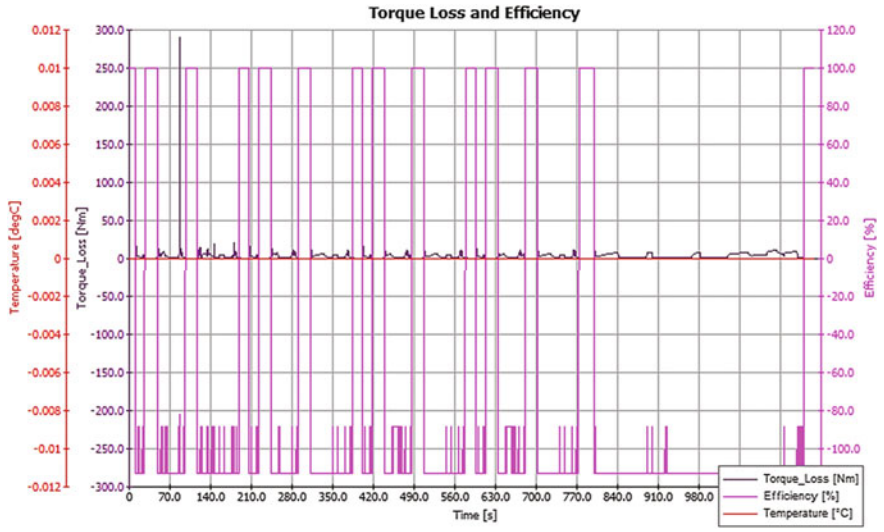


Fig. 5.93 Torque loss and efficiency

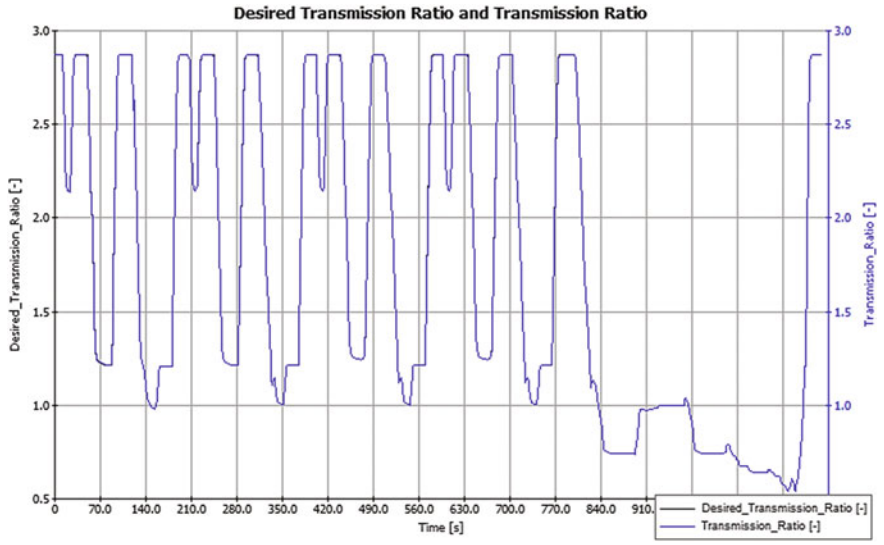


Fig. 5.94 Desired transmission ratio and transmission ratio

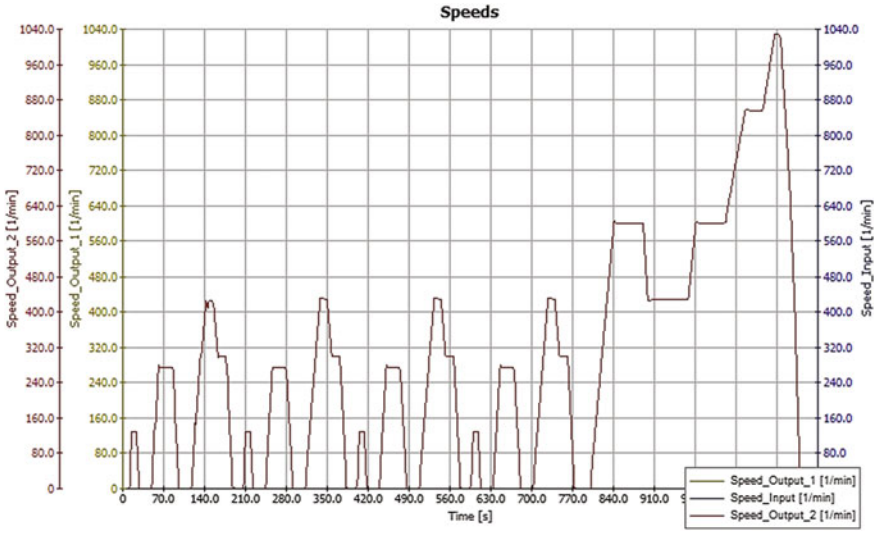


Fig. 5.95 Input and output speeds

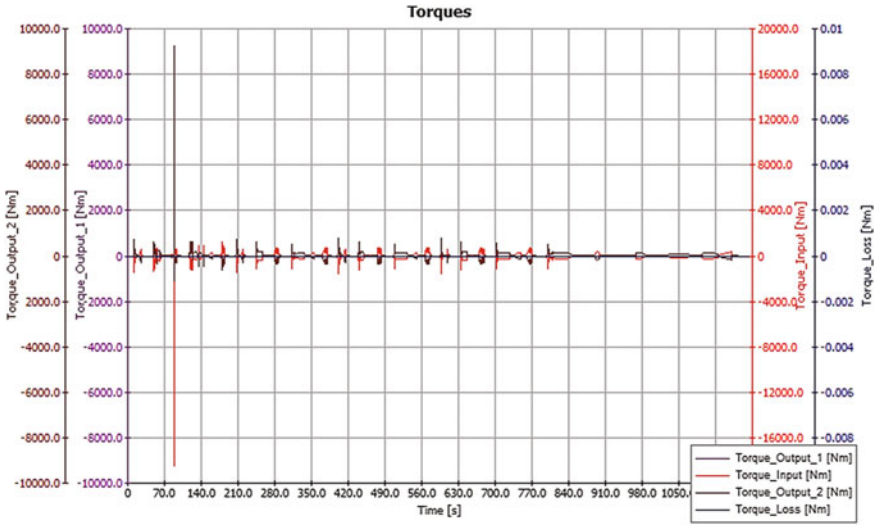


Fig. 5.96 Torque inputs and outputs

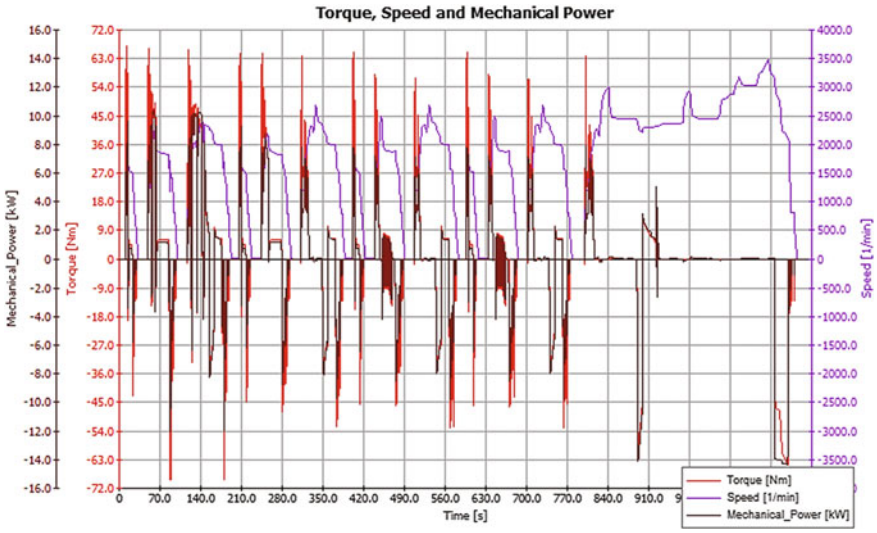


Fig. 5.97 Torque, speed, and mechanical power

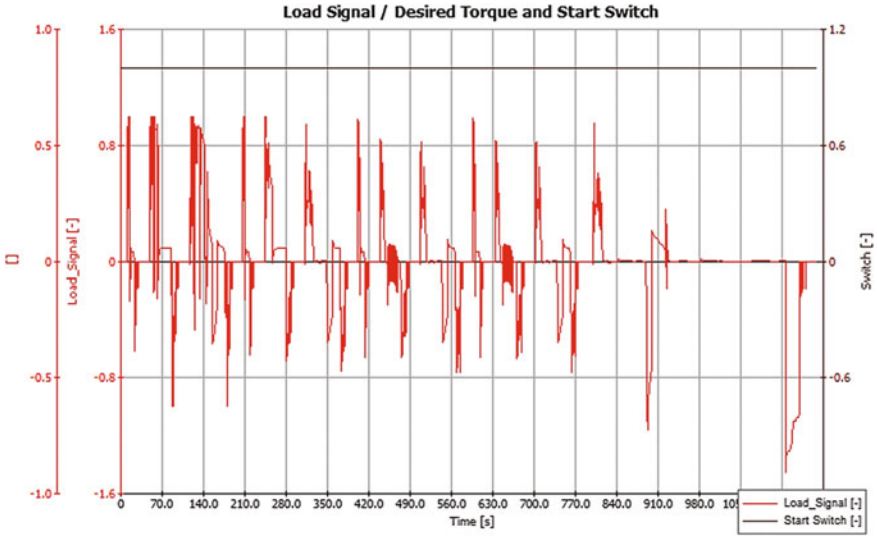


Fig. 5.98 Load signal, desired torque, and start switch

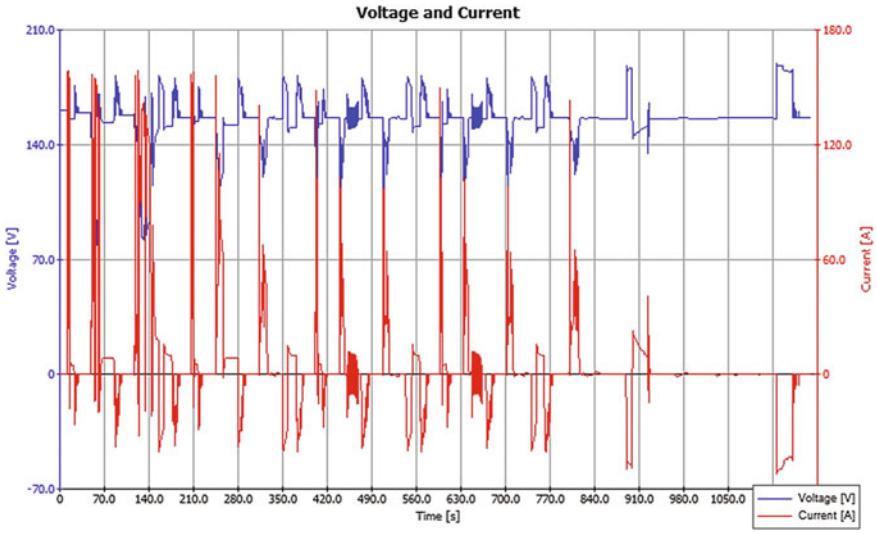


Fig. 5.99 Motor voltage and current

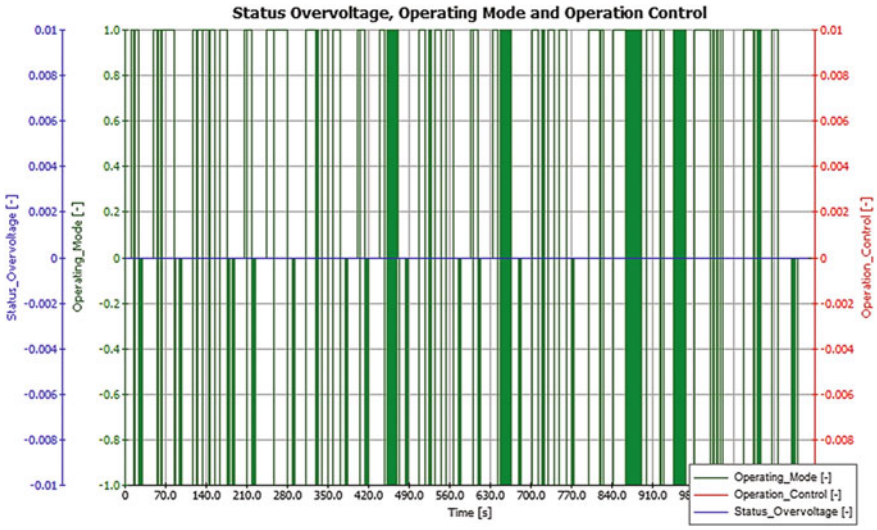


Fig. 5.100 Status overvoltage, operating mode, and operation control

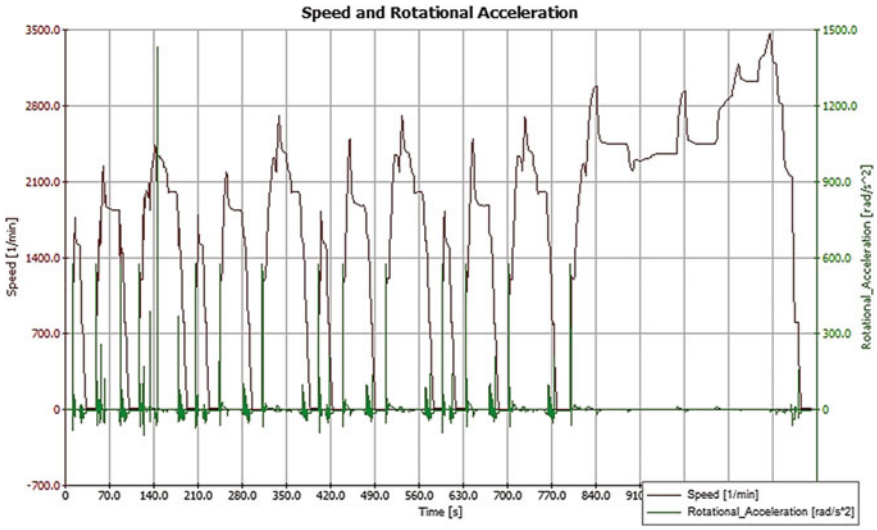


Fig. 5.101 Speed and rotational acceleration

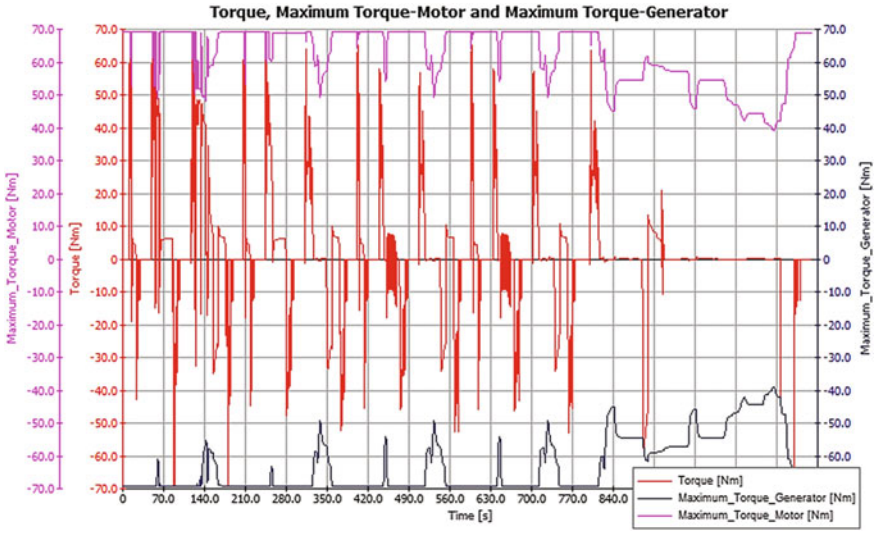


Fig. 5.102 Torque, maximum torque generator, and maximum torque motor

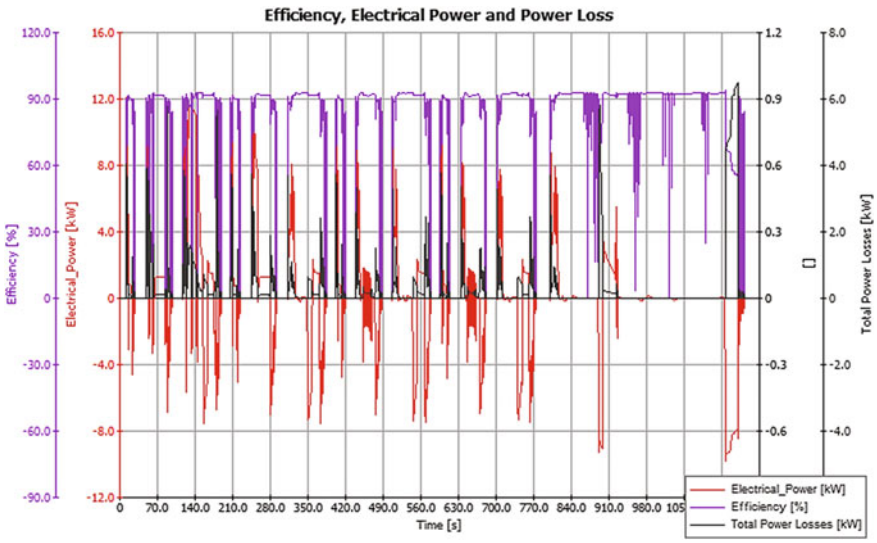


Fig. 5.103 Efficiency, electrical power, and power loss

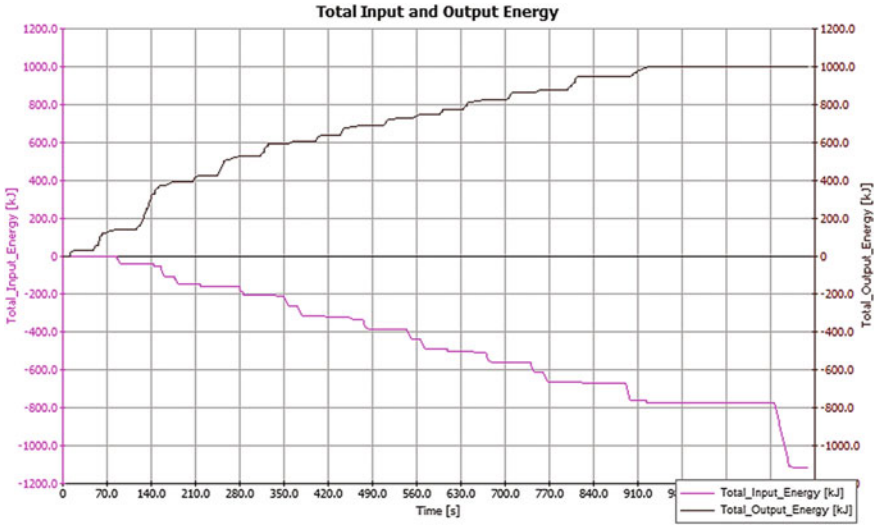


Fig. 5.104 Total input and output energy

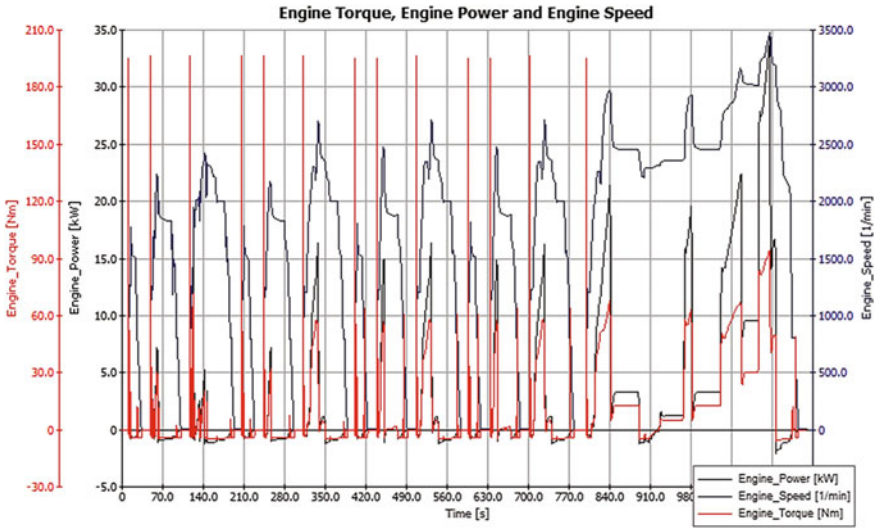


Fig. 5.105 Engine torque, power, and speed

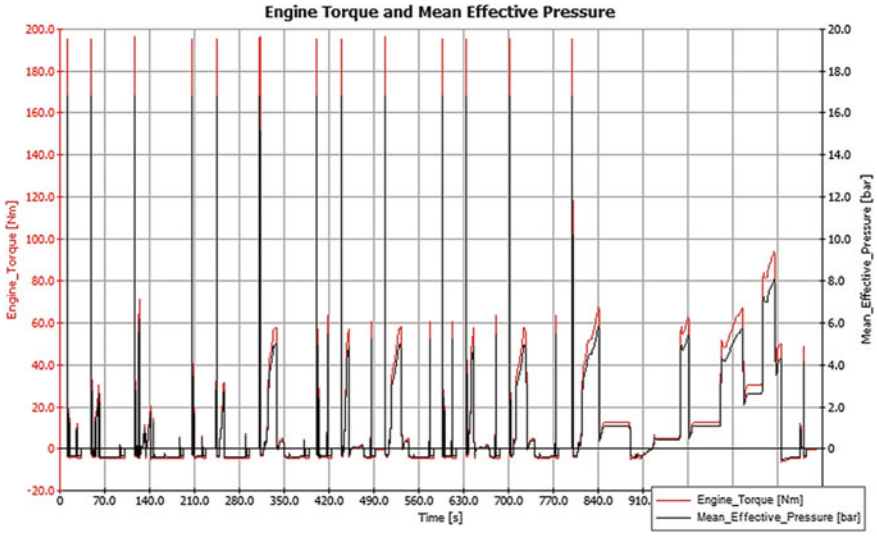


Fig. 5.106 Engine torque and mean effective pressure

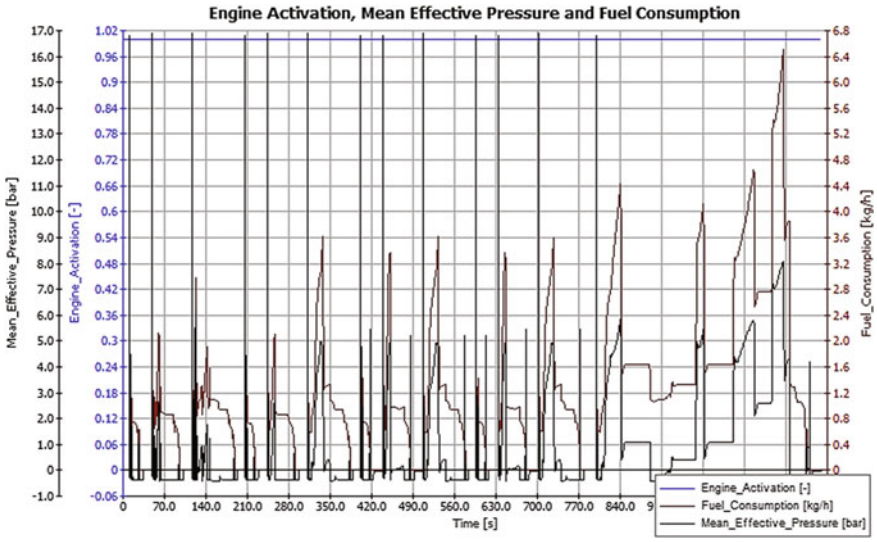


Fig. 5.107 Engine activation, mean effective pressure, and fuel consumption

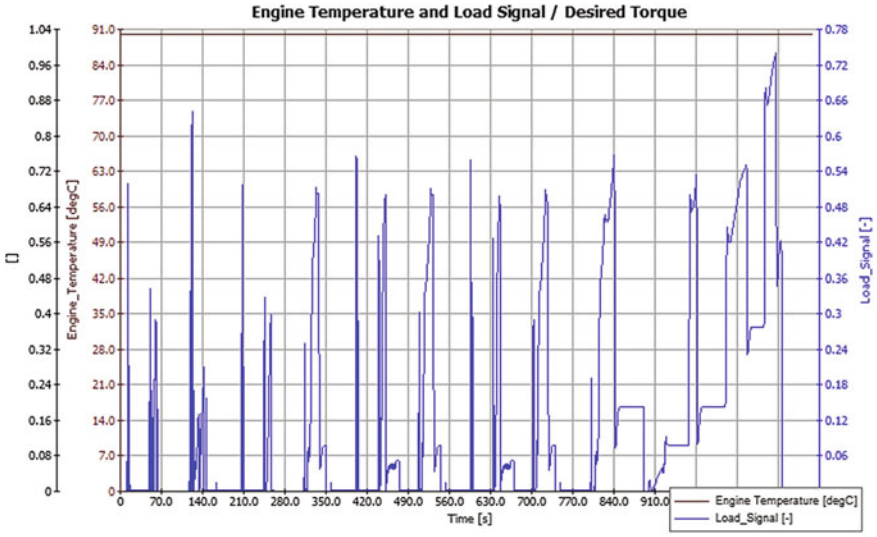


Fig. 5.108 Engine temperature and load signal

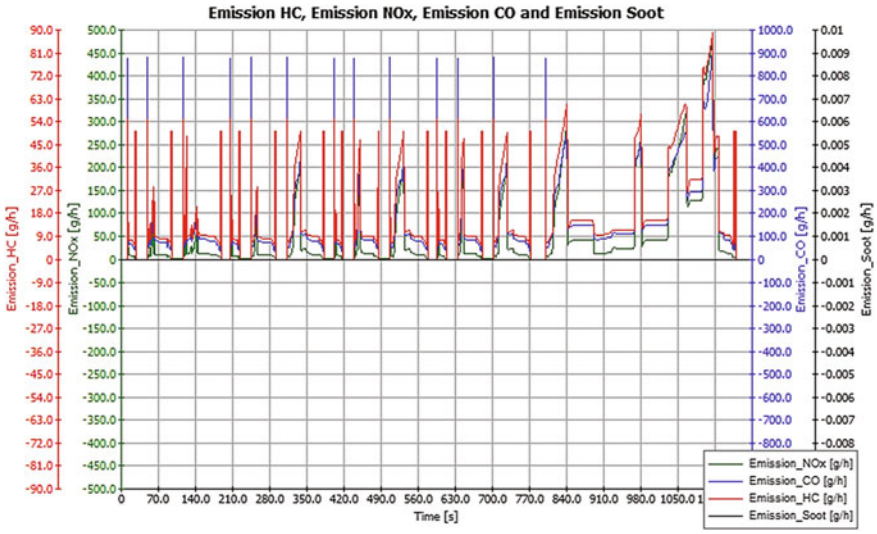


Fig. 5.109 HC, NOx, CO, and Soot emissions

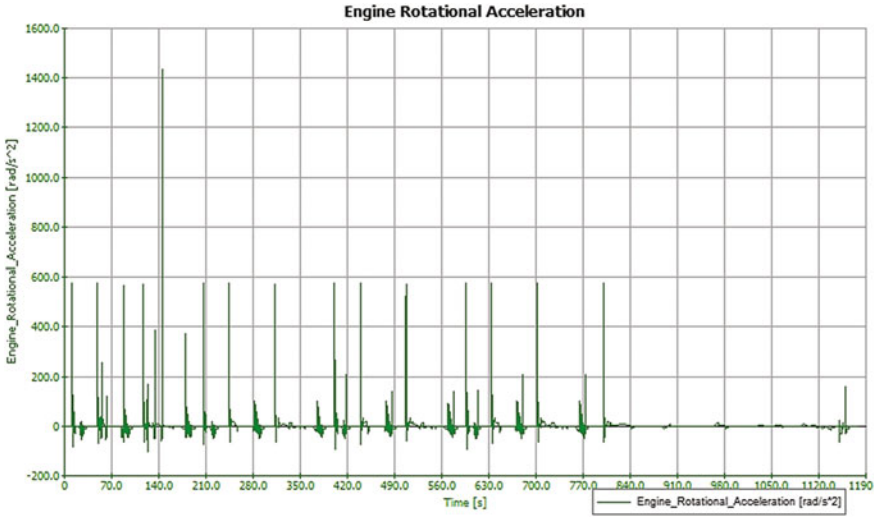


Fig. 5.110 Engine rotational acceleration

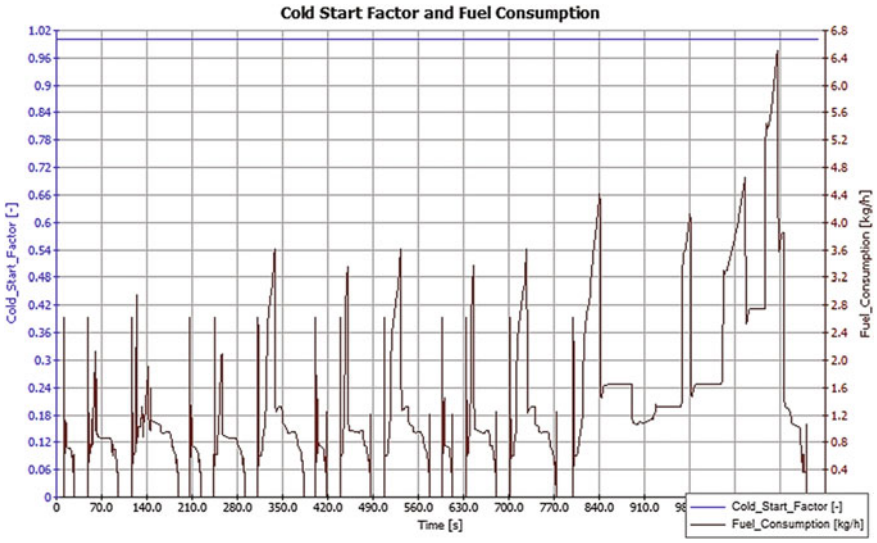


Fig. 5.111 Cold start factor and fuel consumption

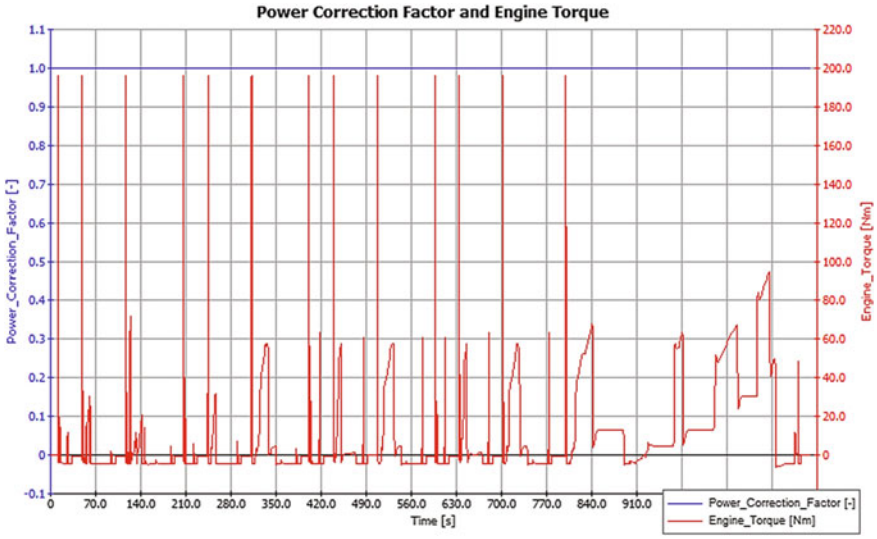


Fig. 5.112 Power correction factor and engine torque

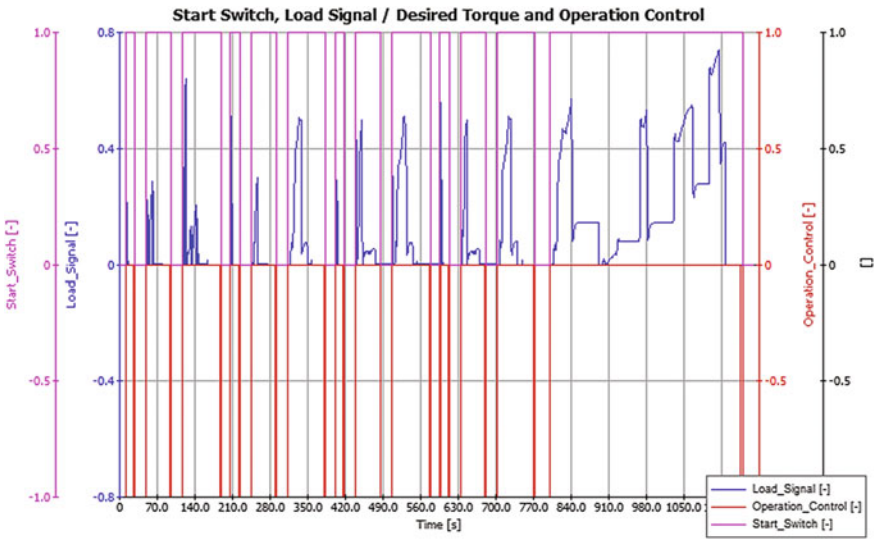


Fig. 5.113 Load signal, operator control, and start switch

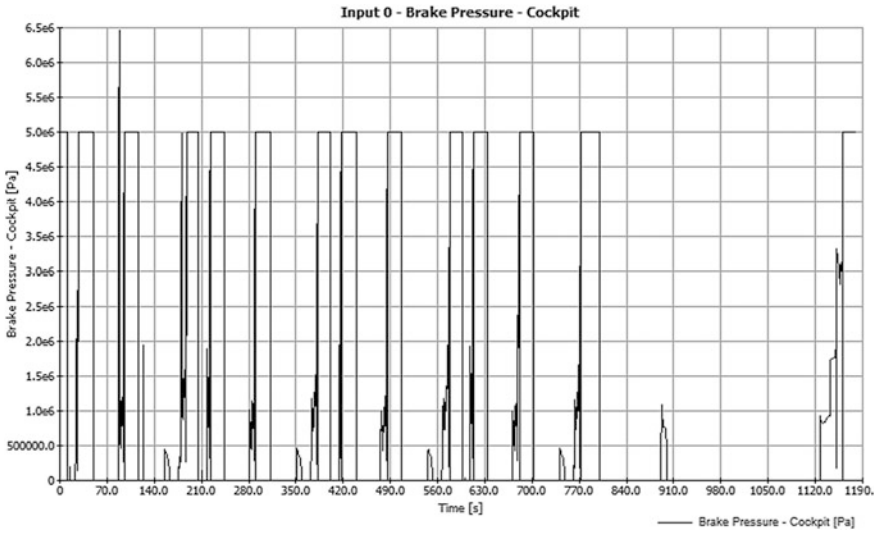


Fig. 5.114 Brake pressure–cockpit

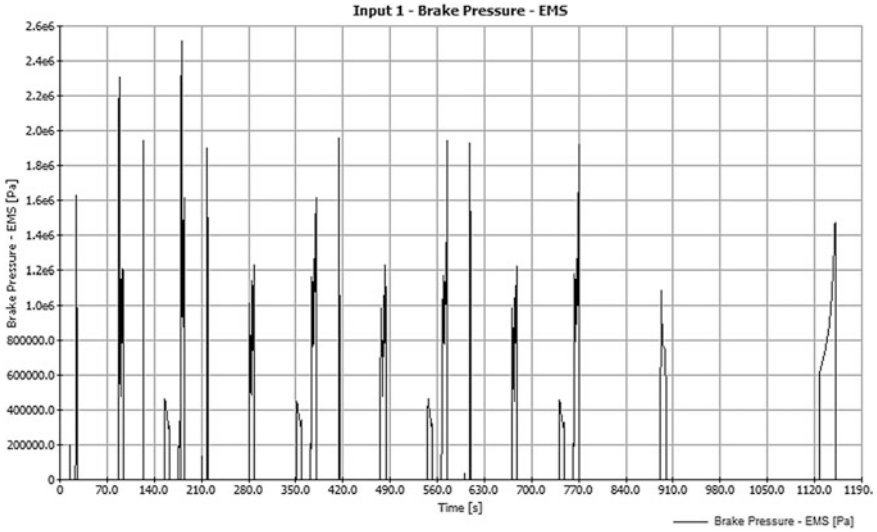


Fig. 5.115 Brake pressure–EMS

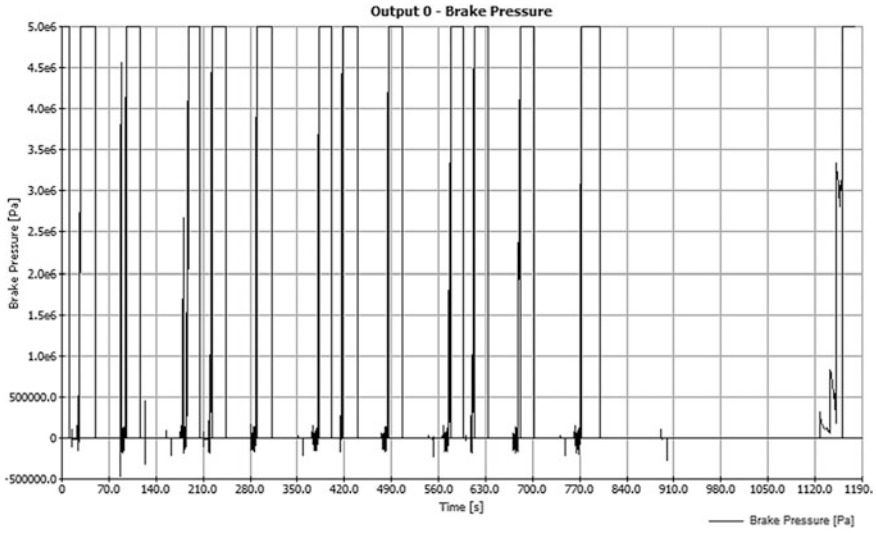


Fig. 5.116 Brake pressure—output

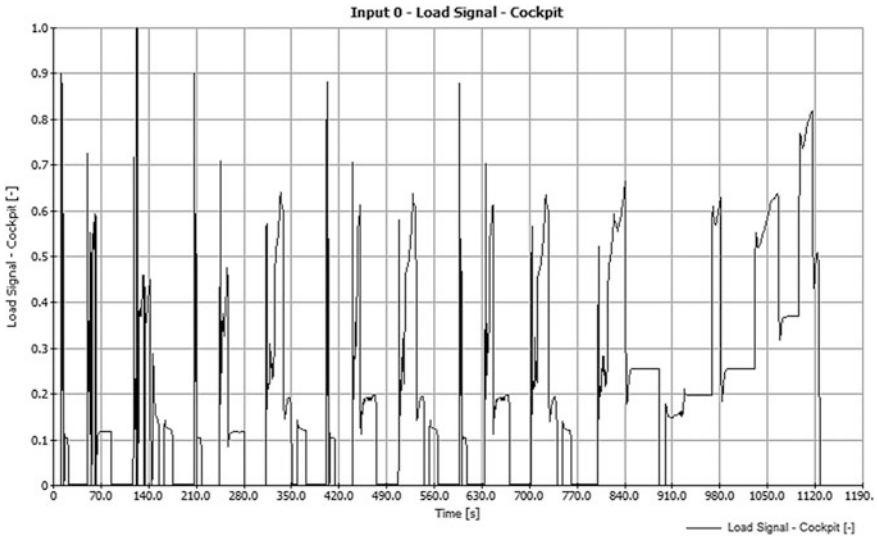


Fig. 5.117 Load signal–cockpit

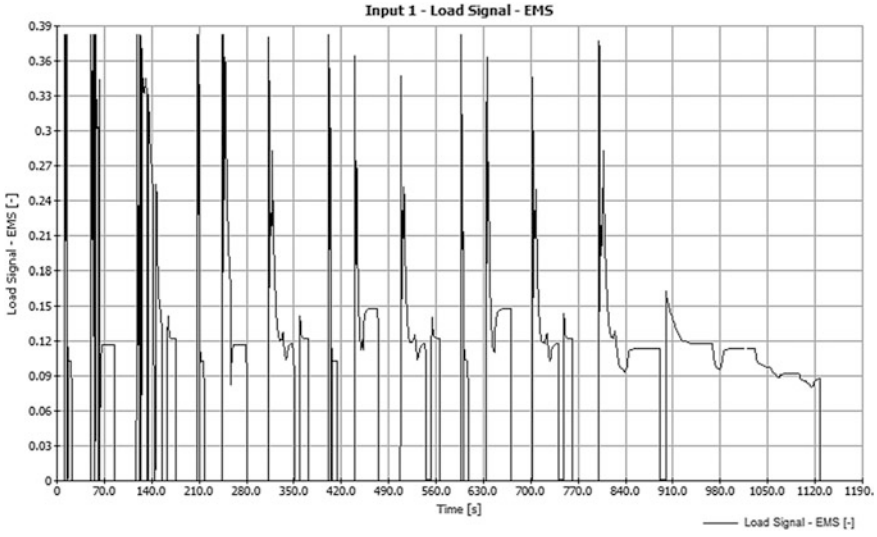


Fig. 5.118 Load signal–EMS

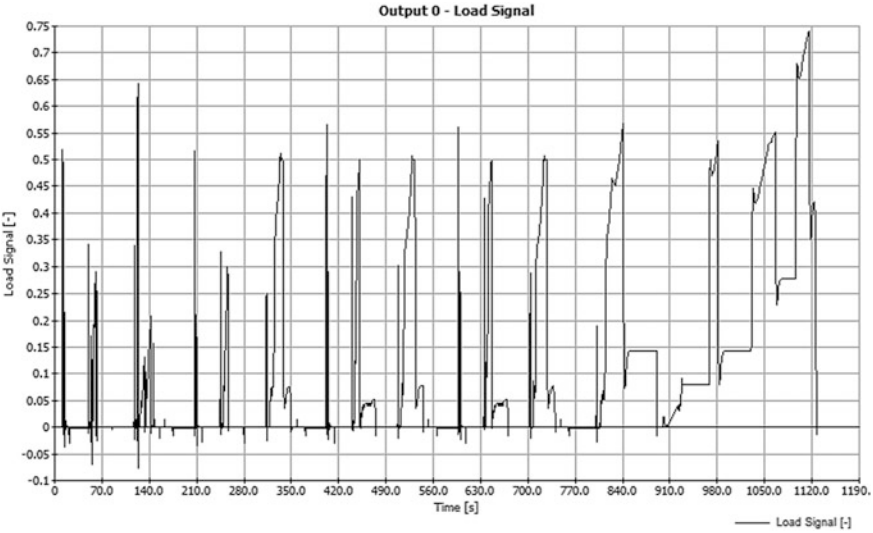


Fig. 5.119 Load signal—output

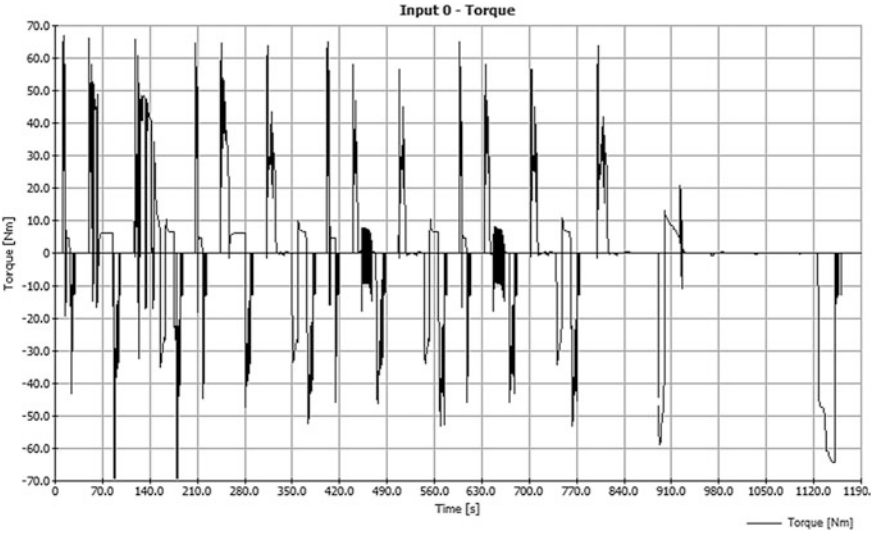


Fig. 5.120 Torque—input

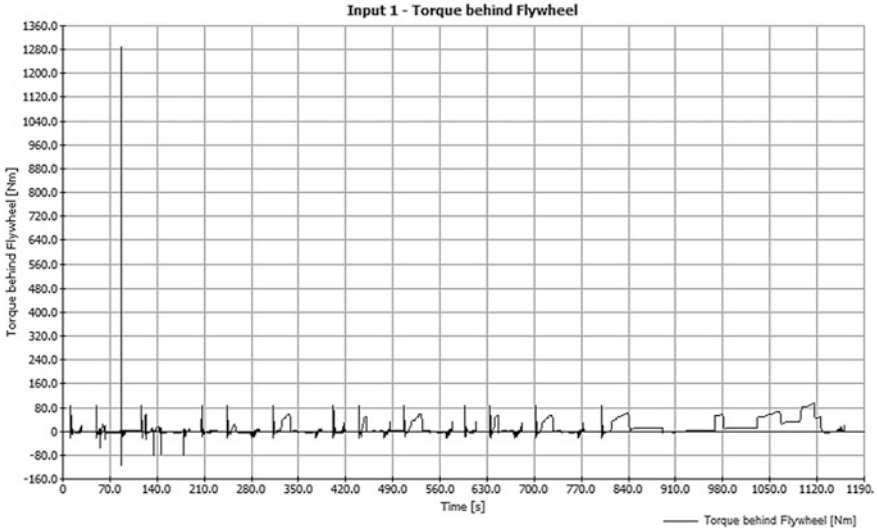


Fig. 5.121 Torque behind flywheel

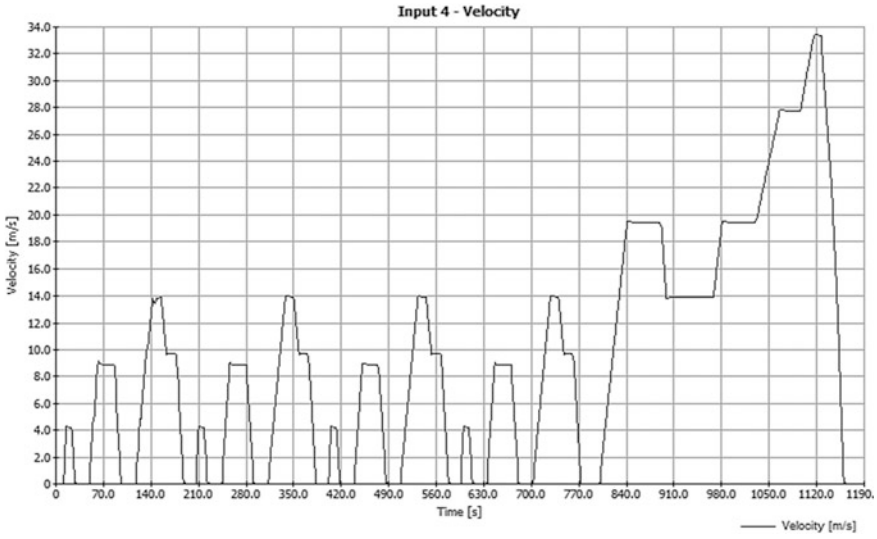


Fig. 5.122 Velocity

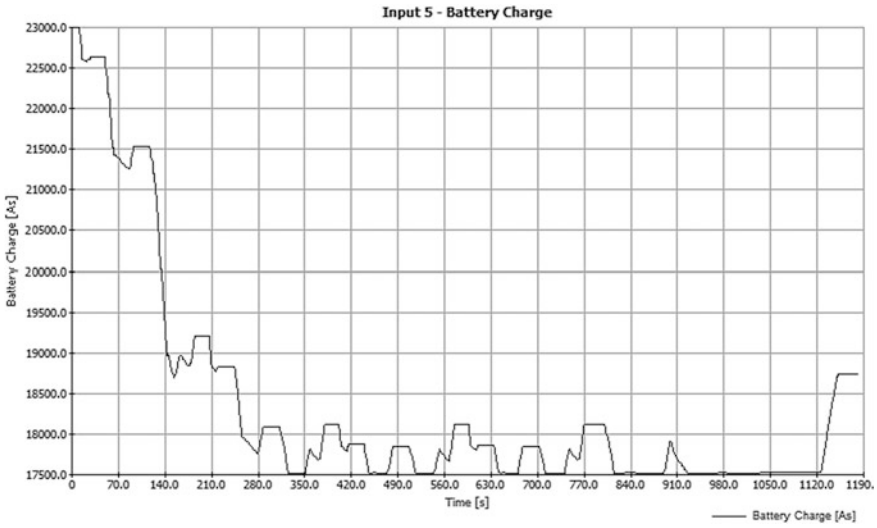


Fig. 5.123 Battery charge

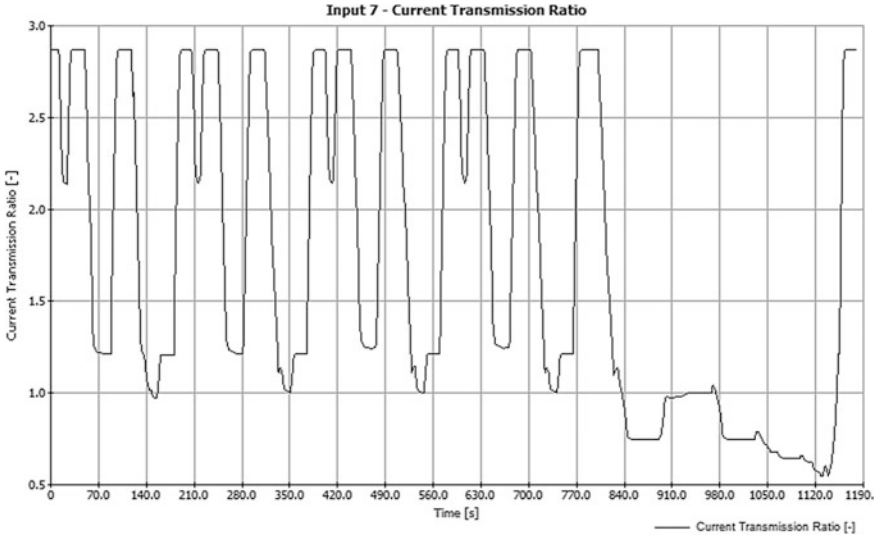


Fig. 5.124 Current transmission ratio

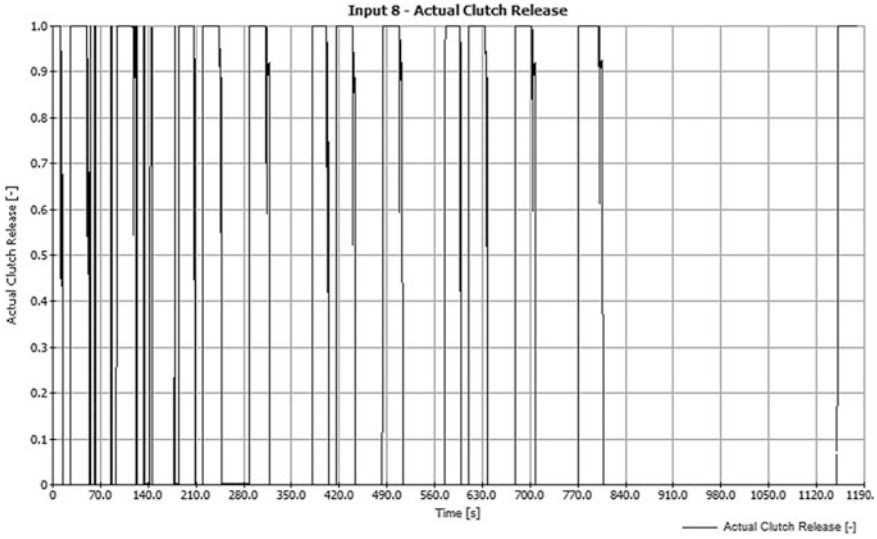


Fig. 5.125 Actual clutch release

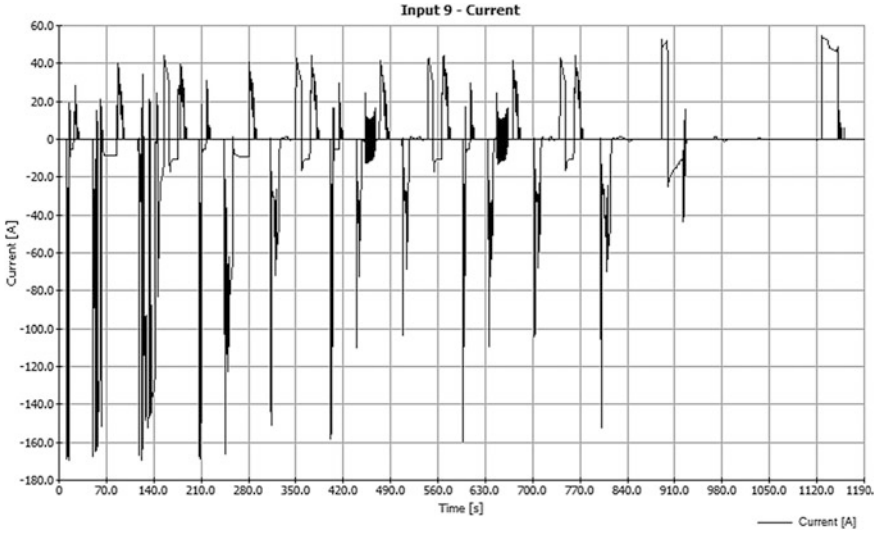


Fig. 5.126 Current—input

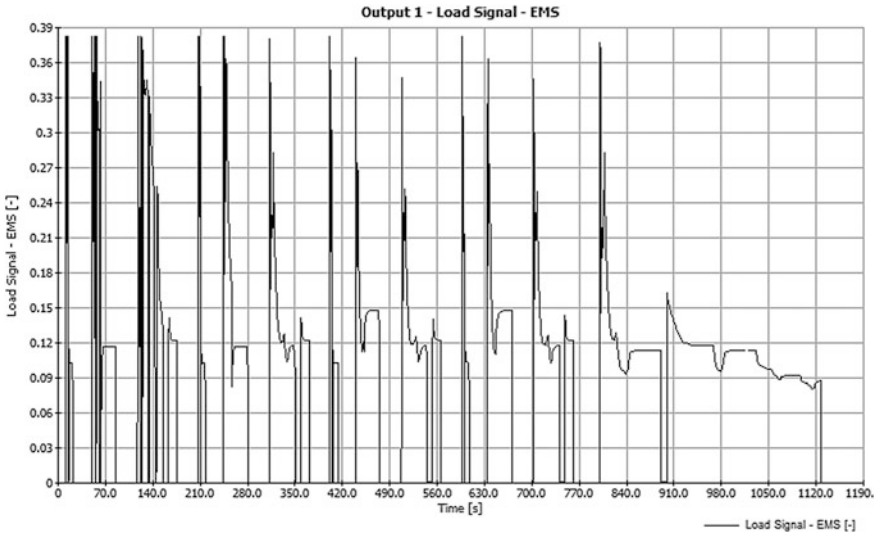


Fig. 5.127 Load signal–EMS—output

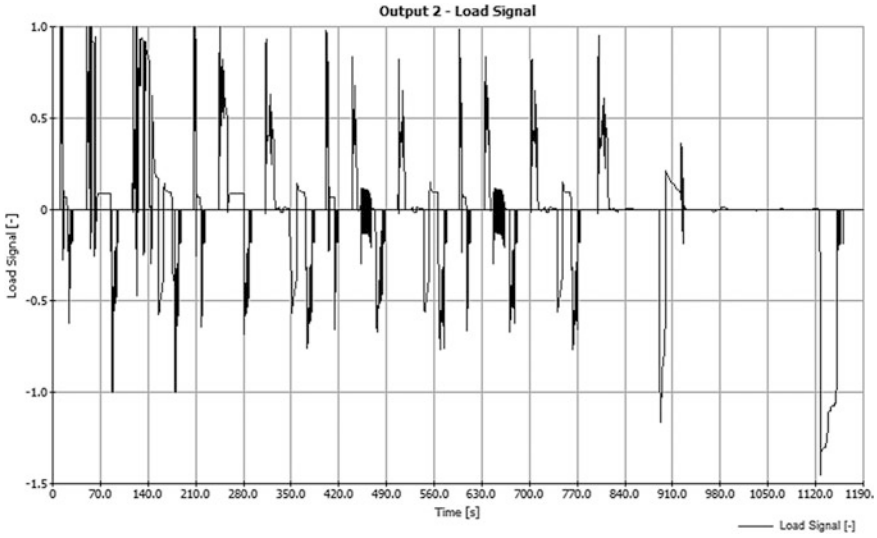


Fig. 5.128 Load signal—output

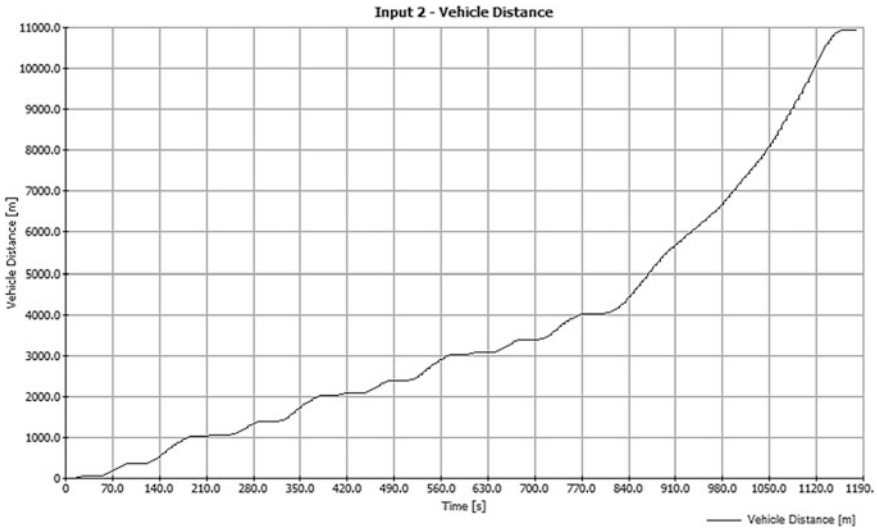


Fig. 5.129 Vehicle distance—input

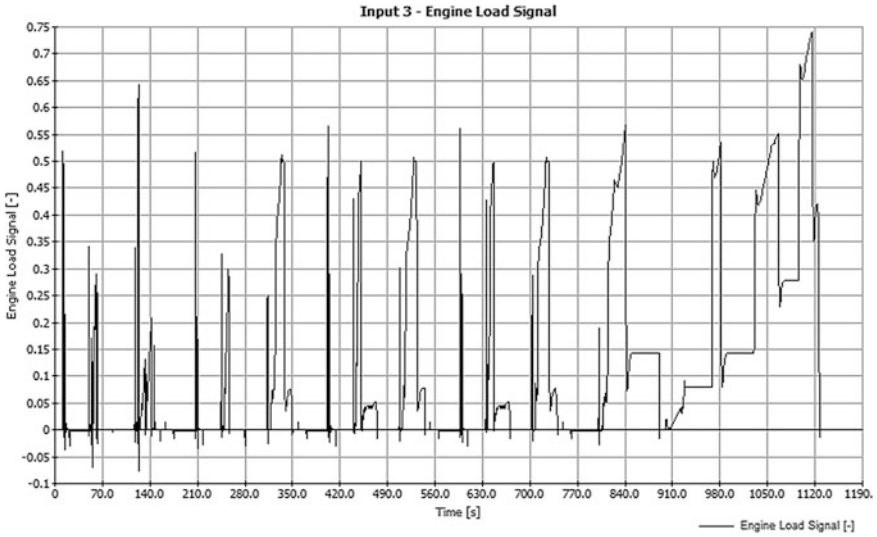


Fig. 5.130 Engine load signal—input

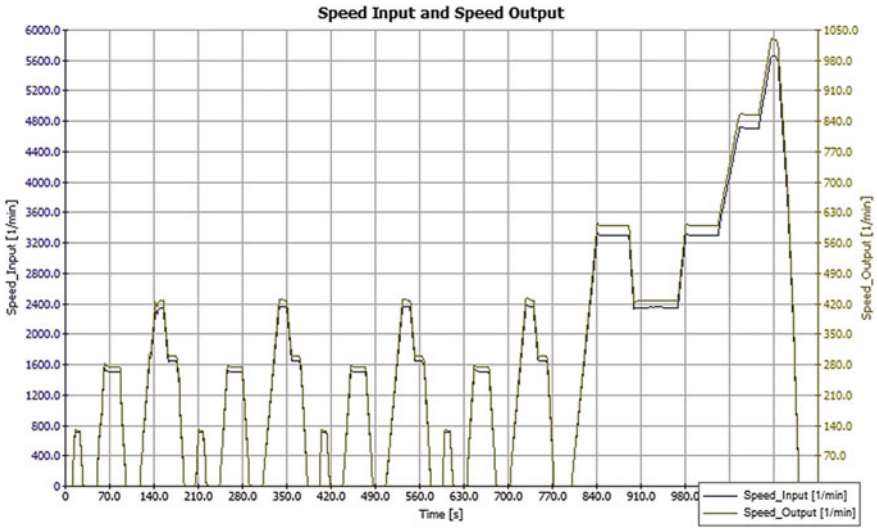


Fig. 5.131 Speed input and output

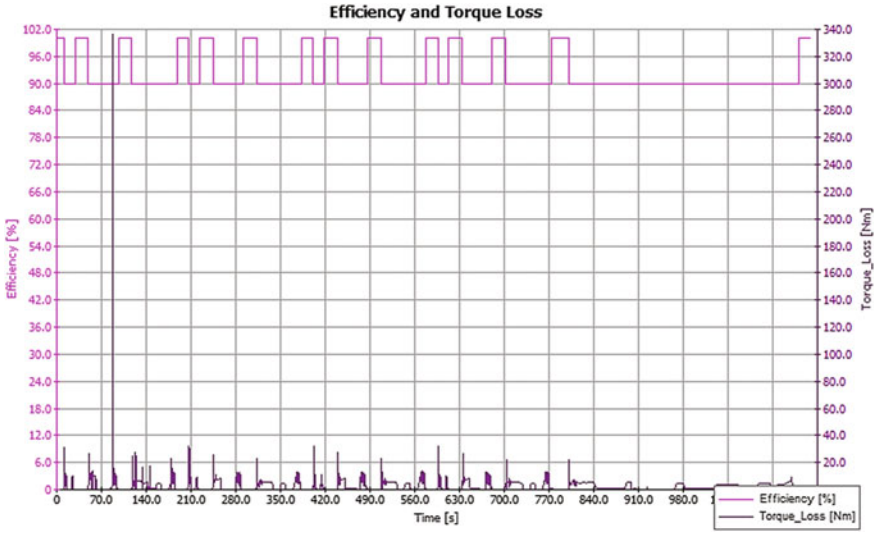


Fig. 5.132 Efficiency and torque loss

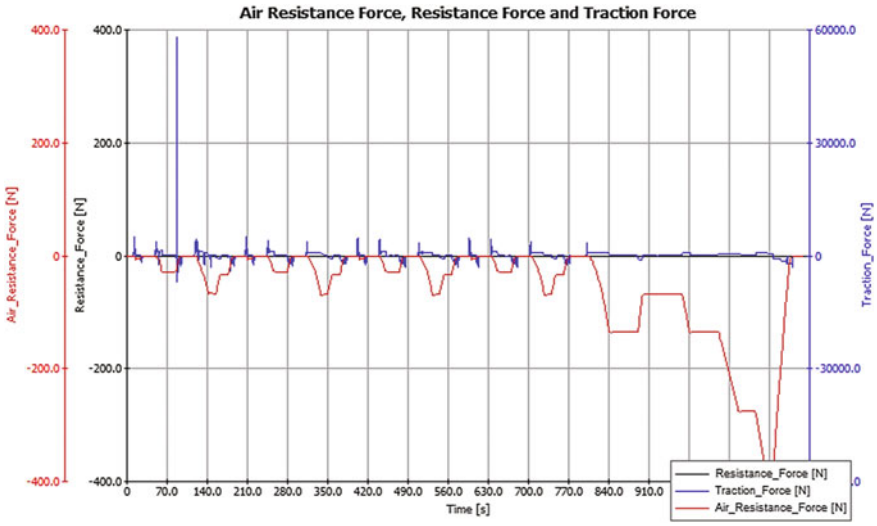


Fig. 5.133 Air resistance force, resistance force, and traction force

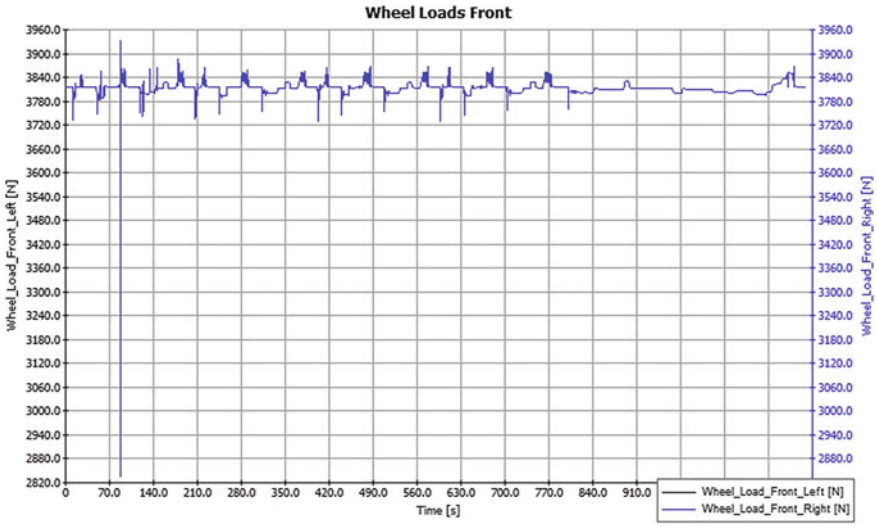


Fig. 5.134 Wheel loads front

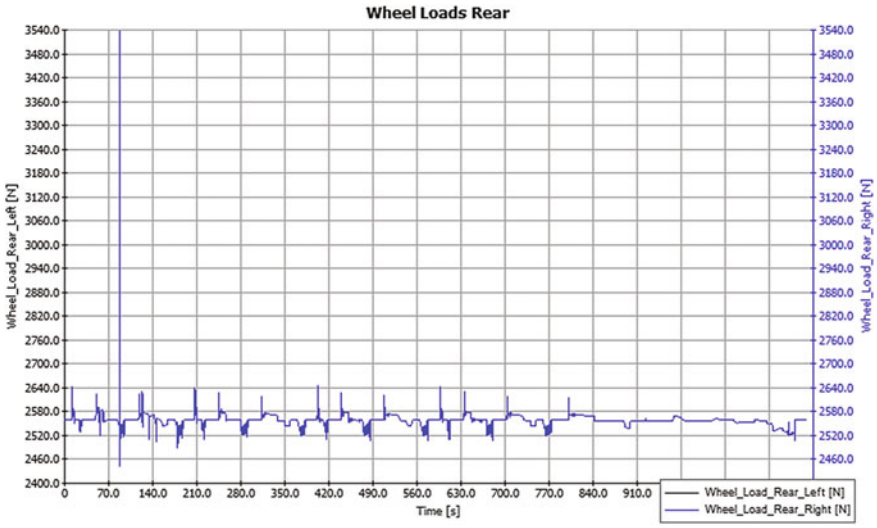


Fig. 5.135 Wheel loads rear

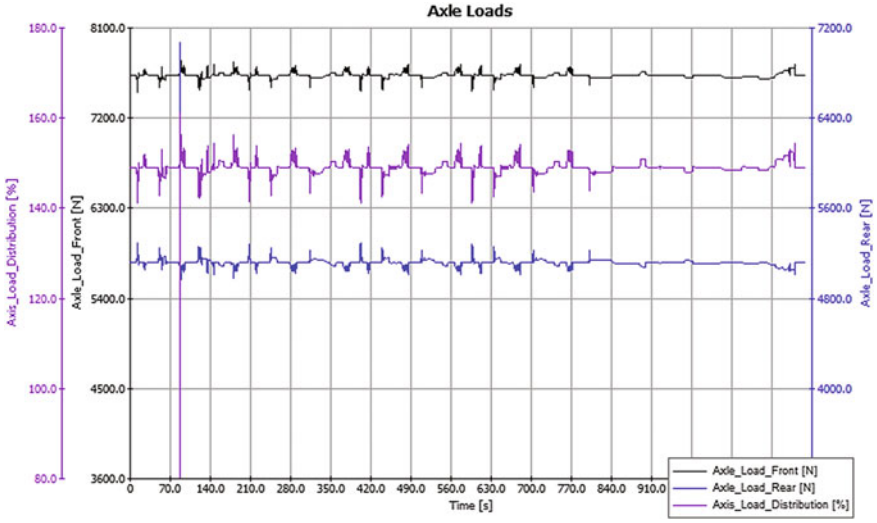


Fig. 5.136 Axle loads

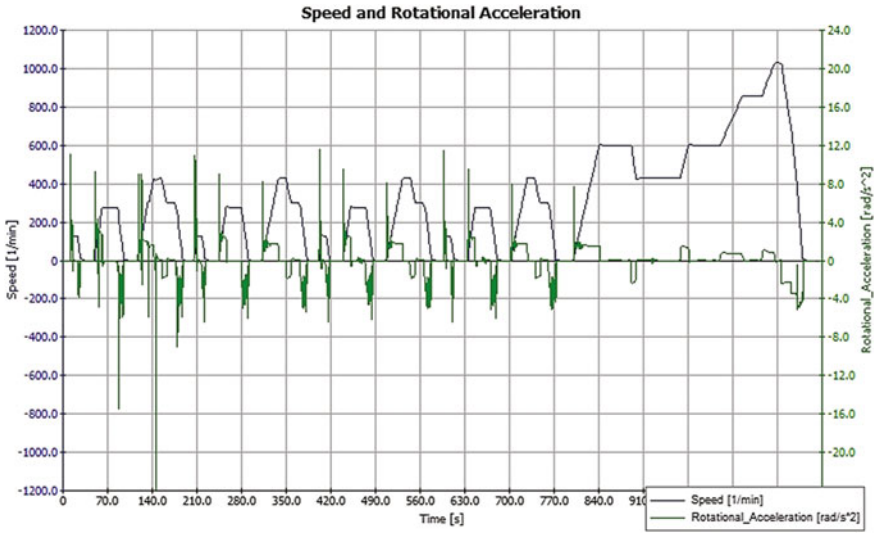


Fig. 5.137 Speed and rotational acceleration

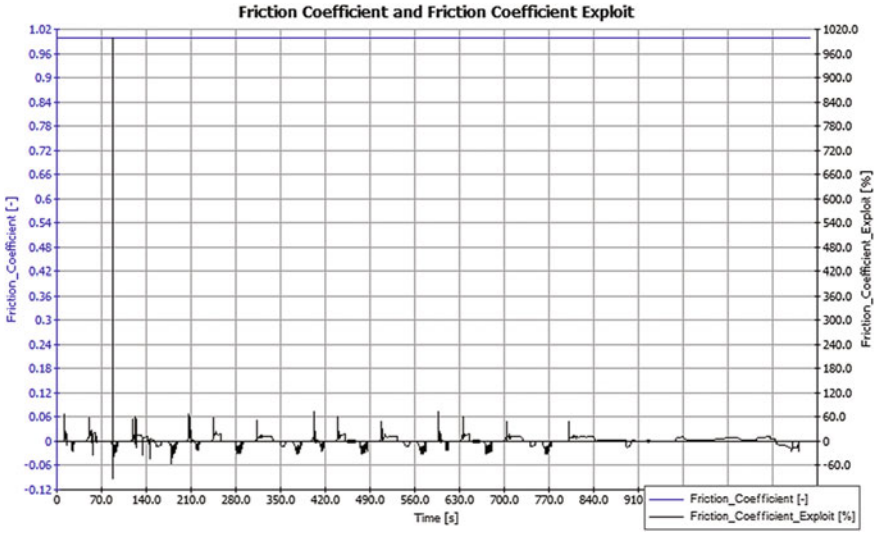


Fig. 5.138 Friction coefficient and friction coefficient exploit

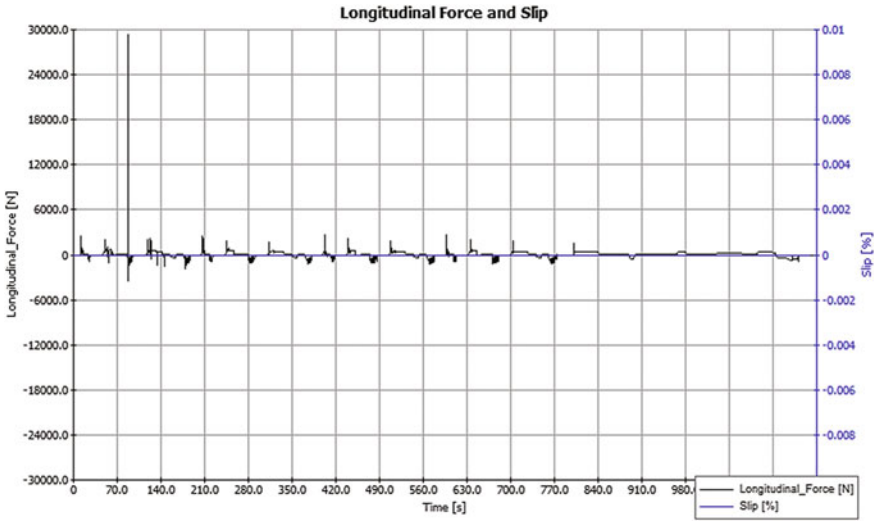


Fig. 5.139 Longitudinal force and slip

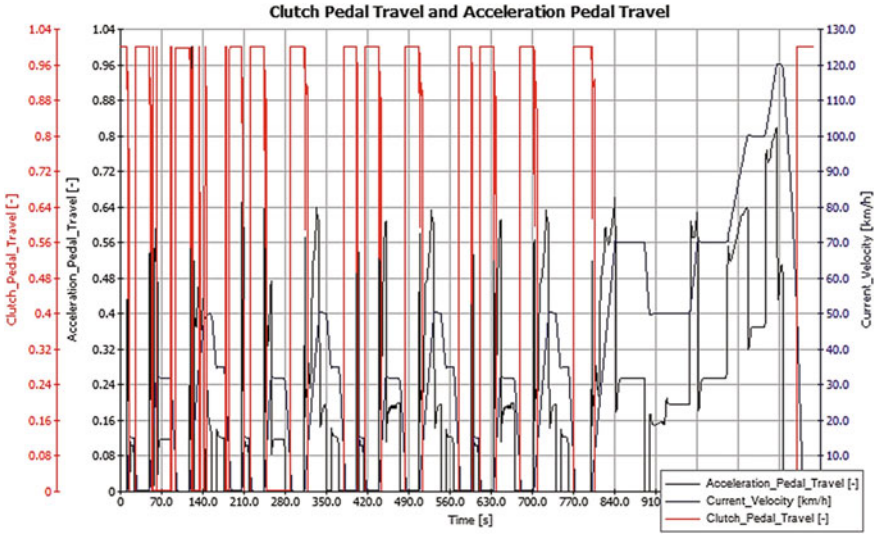


Fig. 5.140 Clutch pedal travel and acceleration pedal travel

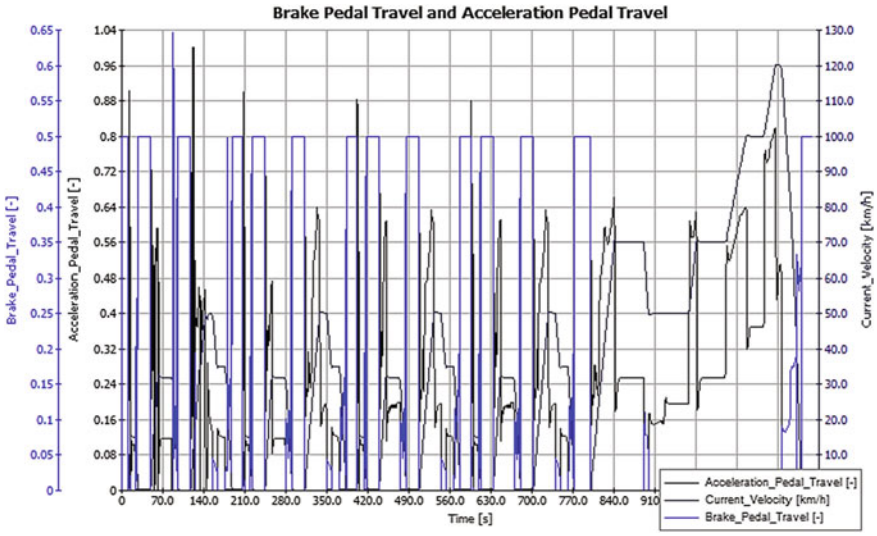


Fig. 5.141 Brake pedal travel and acceleration pedal travel

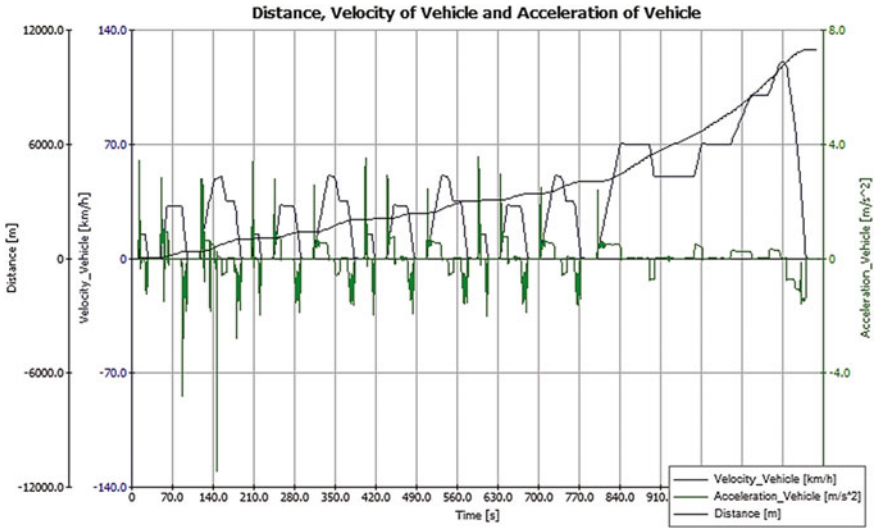


Fig. 5.142 Distance, velocity, and acceleration of the vehicle

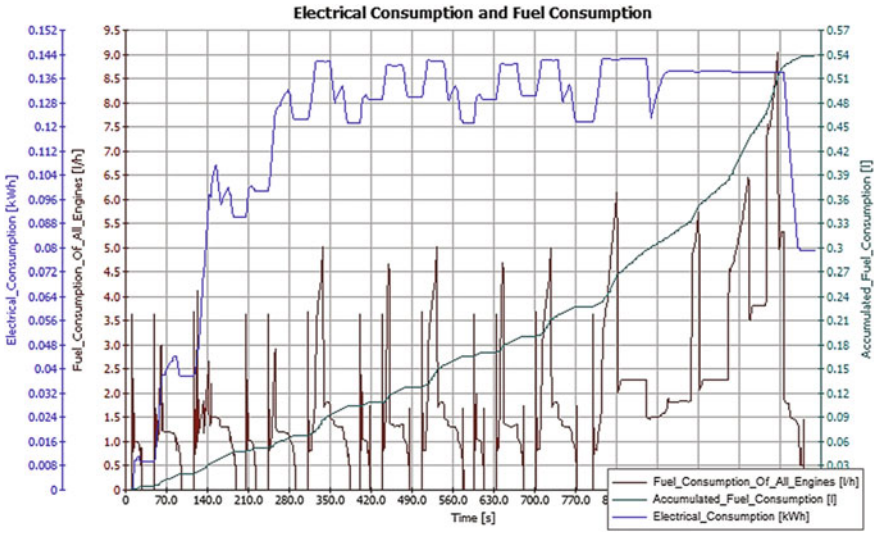


Fig. 5.143 Electrical consumption and fuel consumption

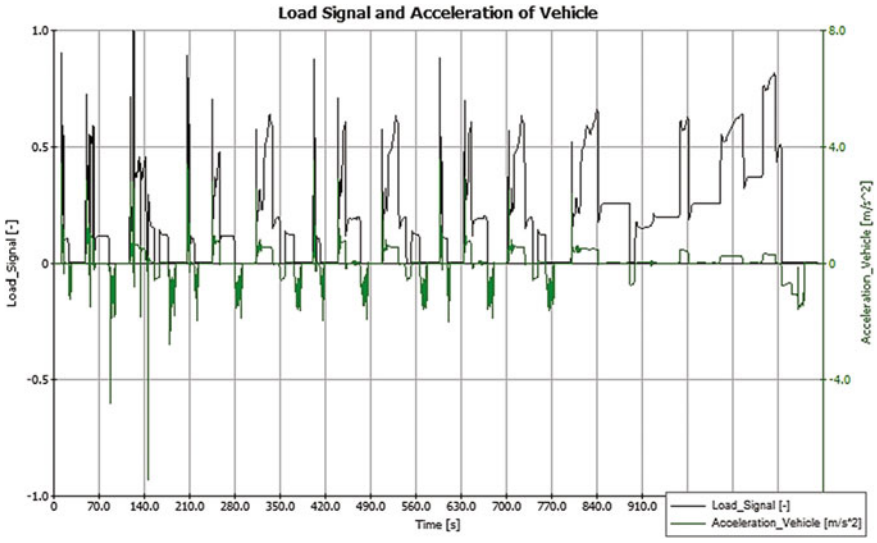


Fig. 5.144 Load signal and vehicle acceleration

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2. AVL Cruise (2011) Users guide. AVL List GmbH, Graz, Austria, Document no. 04.0104.2011, Edition 06.2011
3. AVL Cruise (2011) Gear shifting program (GSP). AVL List GmbH, Graz, Austria, Document no. 04.0114.2011, Edition 06.2011

Chapter 6
Electric Powertrain Configuration Model and Simulation

6.1 Electric Vehicle Model Creation

6.1.1 Electric FWD Model

This chapter describes how to create and run the model of an electric front-wheel drive. To place a component in the working area, click on the component group with the left mouse button, move the mouse over the required component, and then click and drag the component into the Vehicle Model area. The components must be arranged as shown in the following figure (Fig. 6.1) and connected as specified in the diagram. All the connections in the Data Bus for this model are described in Table 6.1 [2].

Place the following components in the working area: Vehicle (1), Final Drive (2), Vehicle Rear Left (3), Vehicle Front Left (4), Vehicle Rear Right (5), Vehicle Front Right (6), Rear Disk Brake (7), Front Disk Brake (8), Rear Disk Brake (9), Front Disk Brake (10), E-Machine (11), Differential (12), Cockpit (13), ASC (14), Electrical Consumer (15), Battery H (16), E-Drive Function (17), E-Brake & M-Brake Function (18), Monitor (19), and Constants (20).

The **Vehicle** (1) is the main object in a model. This component contains general data of the vehicle, such as nominal dimensions and weights. The aerodynamic, rolling, climbing, acceleration, and total resistance are calculated [1].

To define component input data (Table 6.2), double click on the icon or click on it by using the right mouse button and select edit (Fig. 6.2).

In the properties window the parameters which have influence on the needed component data input for calculation are selected (Fig. 6.3).

Final Drive or **Single Ratio Transmission** (2) is a gear step with fixed ratio (Fig. 6.4). It can be used as a transmission step of the differential. To define component input data, double click on the final drive icon and enter the following data (Table 6.3).

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_6

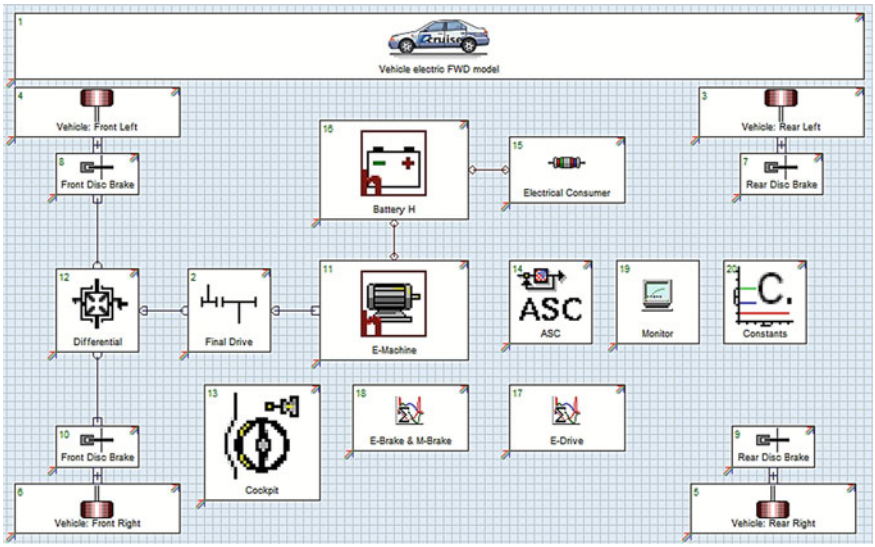


Fig. 6.1 Complete electric FWD model

The **Wheel** component considers many influencing variables and their effect on the rolling state (Fig. 6.5). The wheels and tires link the vehicle to the road.

Information data for the four wheels is the same (Vehicle Rear Left (3), Vehicle Front Left (4), Vehicle Rear Right (5), and Vehicle Front Left (6)). Double click on the wheel and enter the following data (Table 6.4) [2].

The **Brake** component is described by brake data and dimensions (Fig. 6.6). Input data for the two front brakes are the same and also the data for the two rear brakes are the same (Rear Disk Brake Left (7), Front Disk Brake Left (8), Rear Disk Brake Right (9), and Front Disk Brake Right (10)). Double click on the brake icon and enter the following data (Table 6.5).

The **E-Machine** (11) component can be used either as an electric motor or as a generator. There are separate characteristic maps for each mode. Together with the battery H, the user can simulate an electric system. For this model, a characteristic map for the efficiency is used to calculate the loss of power [1]. Double click on the e-machine icon and enter the following data (Table 6.6 and Fig. 6.7).

The value of the voltage level has been measured and should be entered in the following characteristic maps of the machine. For each level, the corresponding voltage value must be defined and the corresponding characteristic maps (voltage for U1 = 100 V, voltage for U1 = 320 V). The maximum mechanical (power) torque (Table 6.7 and Fig. 6.8) is defined as a function of the machines speed (a—speed (1/min), b—torque (Nm)) [2]. Efficiency map is dependent on speed and power (or torque) and is shown in Table 6.8 and Fig. 6.9.

The **Differential** (12) is a particular type of simple planetary gear train that has the property that the angular velocity of its carrier is the average of the angular

Table 6.1 Data Bus connections

Component requires	Input information	Component delivering	Output information
ASC	Clutch Release	Cockpit	Course Ambient
	Load Signal	Cockpit	Load Signal
	Slip Signal Front Left	Wheel Front Right	Slip Signal
	Slip Signal Front Right	Wheel Front Left	Slip Signal
	Slip Signal Rear Left	Wheel Front Right	Slip Signal
	Slip Signal Rear Right	Wheel Front Left	Slip Signal
Battery H	Ambient Temperature	Cockpit	Course Ambient
	Temperature External	Cockpit	Course Ambient
Brake Rear Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Front Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Rear Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Front Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Cockpit	**Gear Indicator**	E-Machine	Operating Mode
	Operation Control 0	E-Machine	Operation Control
	Speed	E-Machine	Speed
E-Machine	Ambient Temperature	Cockpit	Course Ambient
	Load Signal	E-Drive	Mod Load Signal
	Temperature External	Cockpit	Course Ambient
Electric Consumer	Set Value X	Battery H	Net Voltage
Function E-Drive	Vehicle Velocity	Cockpit	Velocity
	Vehicle Acceleration	Cockpit	Acceleration
	Load Signal	Cockpit	Load Signal
	Brake Pressure	Cockpit	Brake Pressure
	Maxim Brake Pressure	Constants	Maxim Brake Pressure
	Bremsfactor	Constants	Brake Factor
E-Brake M-Brake	eDrive_Torque	E-Machine	Torque
	iFD	Constants	iFD
	iTR	Constants	iTR
	Brake_Factor_Front	Constants	Brake_Factor_Front
	Brake_Factor_Rear	Constants	Brake_Factor_Rear
	Brake_Pressure_Driver	Cockpit	Brake Pressure
Monitor	LoadSignal_Cockpit	Cockpit	Load Signal
	Velocity	Cockpit	Velocity
	Torque eDrive	E-Machine	Torque

velocities of its sun and annular gears (Fig. 6.10). To define component input data, double click on the differential icon and enter the following data (Table 6.9).

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component. All mechanical connections starting from the selected component are shown in a tree-structure in the left side of the window (Fig. 6.11).

Table 6.2 Vehicle component input data

Name	Value	Unit
Distance from Hitch to Front Axle	2400	mm
Height of Support Point at Bench Test	500	mm
Wheel Base	2400	mm
Distance of Gravity Center empty	1200	mm
Distance of Gravity Center half	1180	mm
Distance of Gravity Center full	1160	mm
Height of Gravity Center empty	500	mm
Height of Gravity Center half	490	mm
Height of Gravity Center full	480	mm
Height of Hitch empty	500	mm
Height of Hitch half	490	mm
Height of Hitch full	480	mm
Tire Pressure Front/Rear Axle	2.40/2.20	bar
Curb/Gross Weight	1200/1500	kg
Frontal Area	2.00	m^2

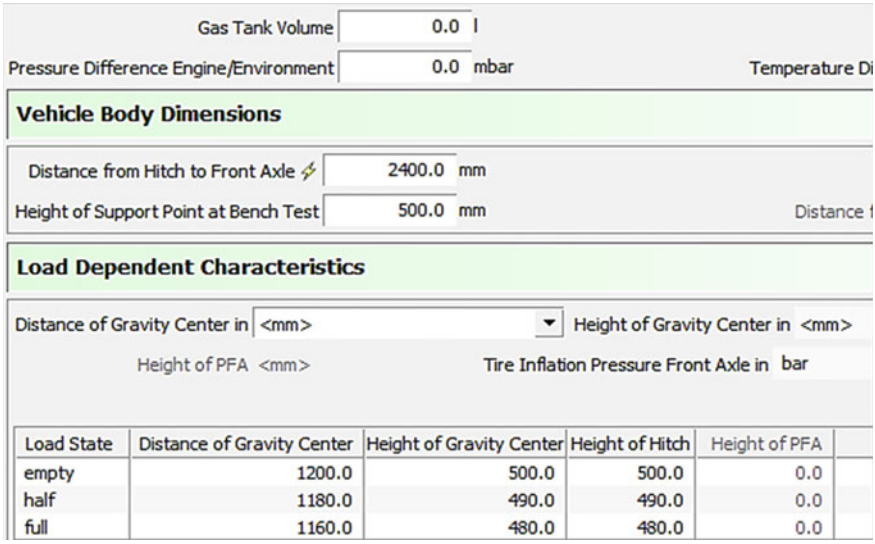


Fig. 6.2 Vehicle input data specifications window

The **Cockpit** (13) links the driver and the vehicle. The pedal positions are transferred into corresponding indicators via the pedal characteristics (Table 6.10).

In this component, connections are only made via the Data Bus (Fig. 6.12).

To define the input data, click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)), clutch pedal characteristic

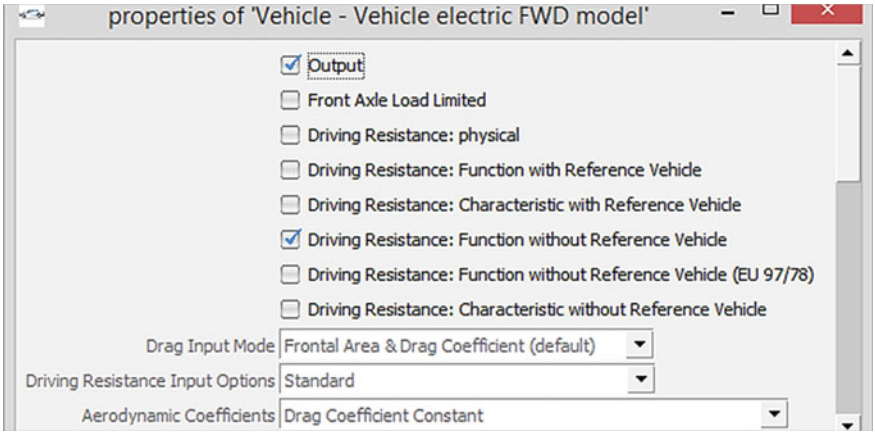


Fig. 6.3 Properties of Vehicle

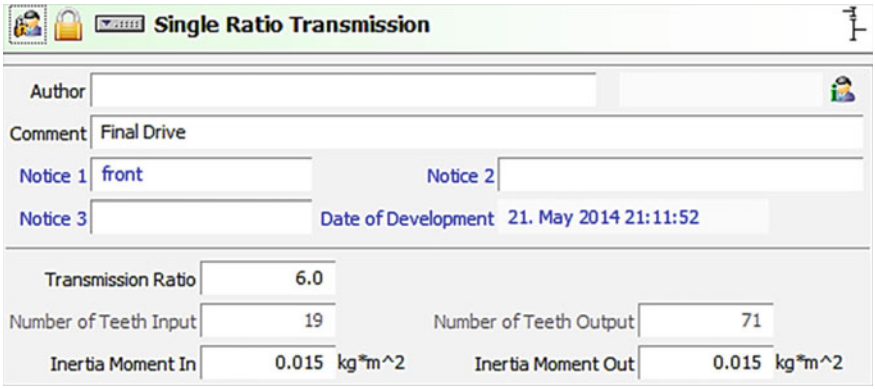


Fig. 6.4 Final Drive input data specifications window

Table 6.3 Final Drive input data

Name	Value	Unit
Transmission Ratio	6.000	–
Inertia Moment In	0.015	kg m^2
Inertia Moment Out	0.015	kg m^2
Efficiency	0.950	–

(a—clutch pedal travel (%), b—clutch release (%)) and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data for all (Fig. 6.13) [2].

The **ASC Anti-Slip Control** (14) checks the force transmission factor of all connected wheels (Fig. 6.14). The Anti-Slip Control is only active when a model is

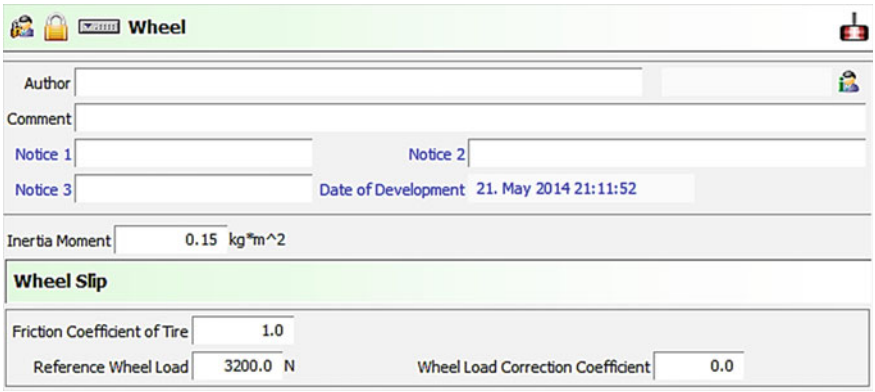


Fig. 6.5 Wheel input data specifications window

Table 6.4 Wheels input data

Name	Value	Unit
Wheel Inertia Moment	0.150	kg m^2
Friction Coefficient of Tire	1.000	–
Reference Wheel Load	3200.0	N
Wheel Load Correction Coefficient	0.000	–
Static Rolling Radius	300.0	mm
Circumference	1884.96	mm
Dynamic Rolling Radius	310.0	mm
Circumference	1947.79	mm

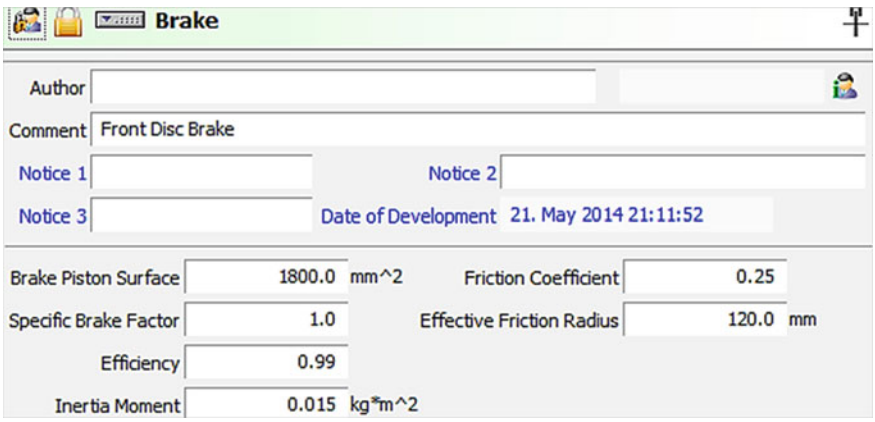


Fig. 6.6 Brake input data specifications window

Table 6.5 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	1800.0	1500.0	1800.0	1500.0	mm^2
Specific Factor	1.000	1.000	1.000	1.000	–
Efficiency	0.990	0.990	0.990	0.990	–
Inertia Moment	0.015	0.015	0.015	0.015	kg m^2
Friction Coefficient	0.250	0.250	0.250	0.250	–
Friction Radius	120.0	100.0	120.0	100.0	mm

Table 6.6 E-Machine input data

Name	Value	Unit
Type of Machine	ASM	–
Characteristic Maps and Curves	Overall	–
Nominal Voltage	320.0	V
Inertia Moment	1.0e−4	kg m^2
Maximum Speed	10000	1/min
Drag Torque at Maximum Speed	0.000	Nm
Initial Temperature	20.00	°C
U1 Voltage	100.0	V
U2 Voltage	320.0	V

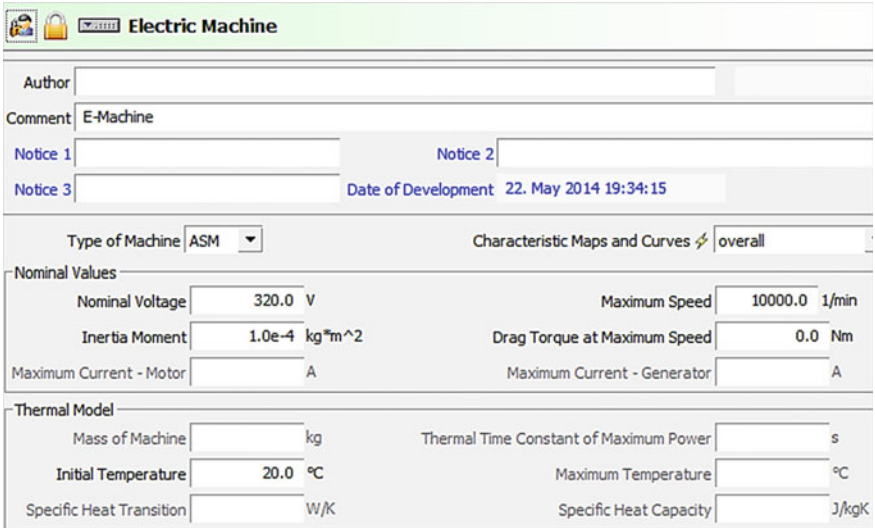


Fig. 6.7 E-Machine input data specifications window

Table 6.7 Maximum mechanical torque data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
0	240	7000	105
500	240	7500	95
1000	240	0	−229
1500	240	750	−229
2000	240	1500	−236
2500	240	2250	−238
3000	240	3000	−239
3500	205	3750	−191
4000	180	4500	−159
4500	160	5250	−136
5000	140	6000	−119
5500	130	6750	−106
6000	120	7500	−95
6500	110	–	–

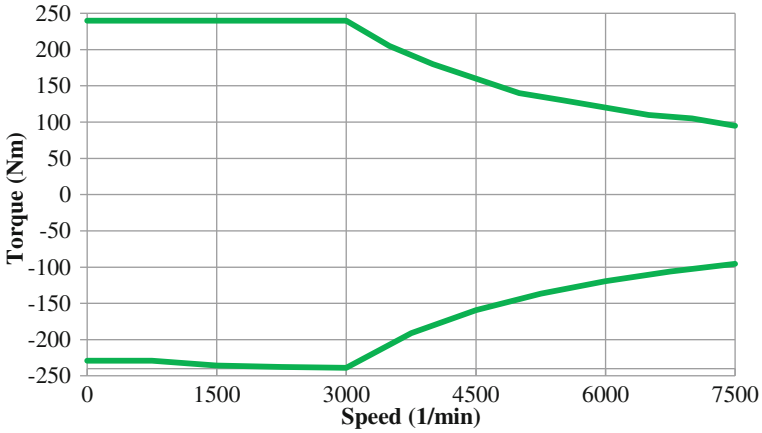


Fig. 6.8 Maximum mechanical torque

calculated quasi-stationary in combination with special drivetrain configurations and does not require data entry [1].

The **Electrical Consumer** (15) is represented as an ohmic resistor in the onboard network (Fig. 6.15). They represent an electric current loss. The number of resistors that can be defined is user dependent [1].

The resistors parameter can be fixed by a constant value or by means of characteristic curves. It is possible to define resistors as a function of any external input value.

Double click on the electrical consumer icon and enter the data (Table 6.11). The electrical consumer can be described as resistance depending on input value a—voltage (V) and b—resistance (Ω) in resistance table (Fig. 6.16 and Table 6.12).

Table 6.8 Efficiency map data

(a)												
500	(b)	0	25	50	75	100	125	–	–	–	–	–
	(c)	65	76	76	75	75	73	–	–	–	–	–
1000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	82	83	83	83	81	80	79	77	76
1500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	86	86	86	86	86	85	84	83	82
2000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	87	88	89	89	88	88	87	86	85
2500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	87	89	90	90	91	90	89	88	88
3000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	88	91	91	91	91	91	90	90	90
3500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	88	91	91	91	92	92	91	91	91
4500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	80	88	91	91	92	93	93	93	93	93
5500	(b)	0	25	50	75	100	125	–	–	–	–	–
	(c)	65	80	88	91	91	93	–	–	–	–	–
6000	(b)	0	25	50	75	100	−95	−80	−65	−45	−35	−15
	(c)	65	80	88	91	91	93	93	92	91	86	75
6500	(b)	0	25	50	75	100	−95	−80	−65	−45	−35	−15
	(c)	65	82	87	90	91	93	93	91	88	82	73
7000	(b)	0	25	50	75	100	−95	−80	−65	−45	−35	−15
	(c)	65	82	86	89	91	93	91	89	86	80	69

The **Battery H** (16) component is used for simulating of electrical vehicles (Fig. 6.17). Double click on the battery H icon and enter the input data (Table 6.13).

The idle voltage—charge (b) is the idle voltage of one cell in charge mode. When there is no electrical consumer; it is a function of the State of Charge SOC (a) (Fig. 6.18 and Table 6.14). The idle voltage—discharge (b) of one cell is the voltage without an electrical consumer, there is no flow of current, and it is a function of the SOC (a) (Fig. 6.19 and Table 6.15) [1].

E-Drive (17) component is a function that can be used to calculate the transition from the electrical machine driving to electrical machine braking (Fig. 6.20).

To define component input data double click on the C code icon and enter the following data for function (Fig. 6.21), and for description of Data Bus (Table 6.16) [1].

E-Brake & M-Brake (18) component is a function that can be used for calculating the converting brake torque into pressure for all brakes (Fig. 6.21).

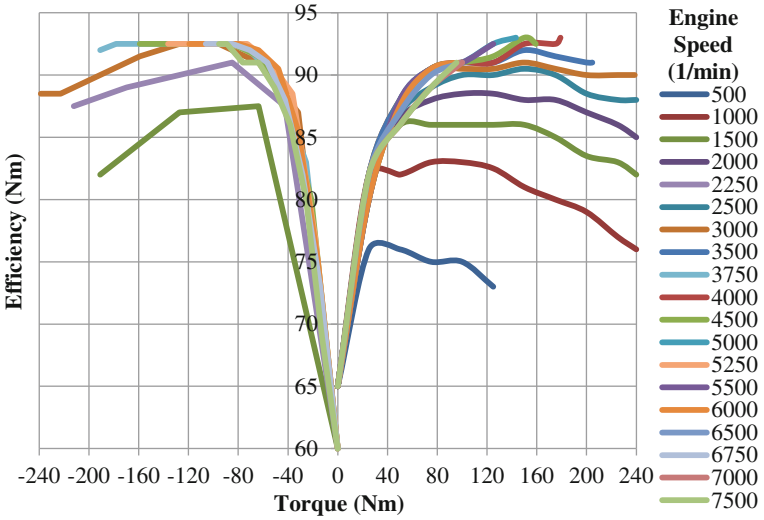


Fig. 6.9 Efficiency map

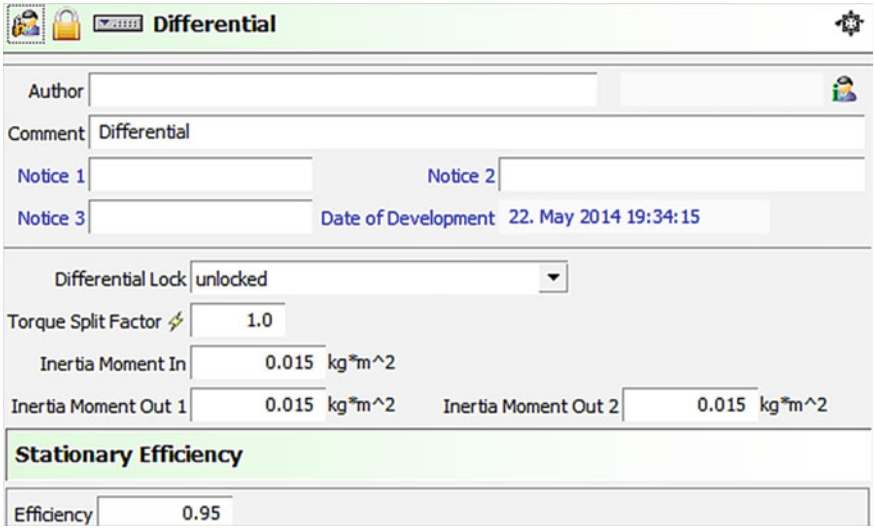


Fig. 6.10 Differential input data specifications window

To define component input data, double click on the C code icon and enter the following data for function (Fig. 6.22), and for description of Data Bus (Table 6.17) [1] (Fig. 6.23).

The **Monitor** component (19) can be introduced, if the calculation run must be detected (Fig. 6.24). Click on the description of Data Bus tab and open the

Table 6.9 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.000	–
Inertia Moment In	0.015	kg m^2
Inertia Moment Out1	0.015	kg m^2
Inertia Moment Out2	0.015	kg m^2

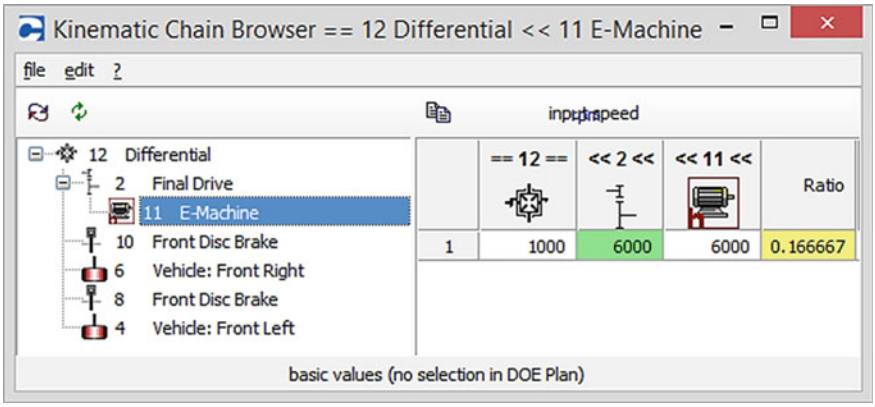


Fig. 6.11 Kinematic Chain Browser

Table 6.10 Cockpit input data

Name	Value	Unit
Shift Mode	Manual	–
Number of Gears Forward	1.000	–
Number of Gears Back	1.000	–
Maximum Brake Force	100.0	N
Brake Light Switch Threshold	1.000	%
Number of Retarder Steps	0.000	–

following dialog. To select a Data Bus channel, click to access at the available list. Enter the text for the description and then click on to select the unit (Table 6.18).

Constants (20) component enables the user to define up to 99 constant values which can be used by other components through the Data Bus. The values can be of type integer, double or string (Table 6.19) [1].

6.1.2 Electric FWD RE Model

This chapter describes how to create and run the model of an electric front wheel drive with range extender. To place a component in the working area, click on the

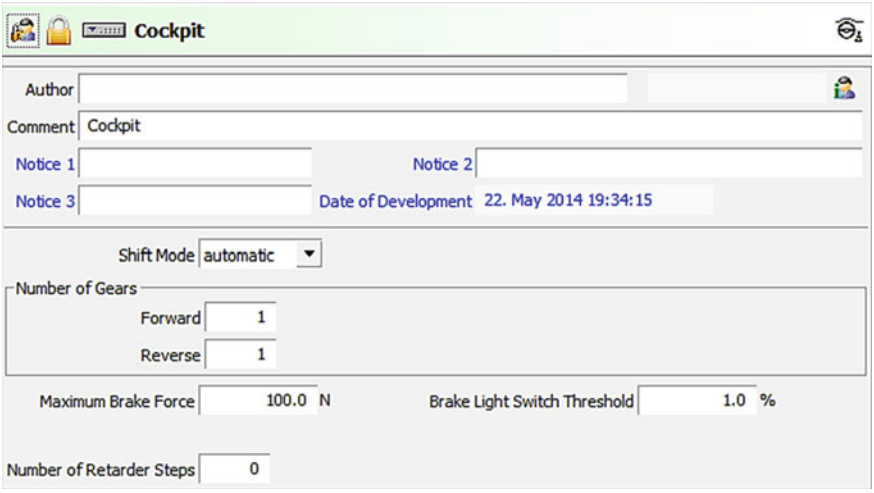


Fig. 6.12 Cockpit input data specifications window

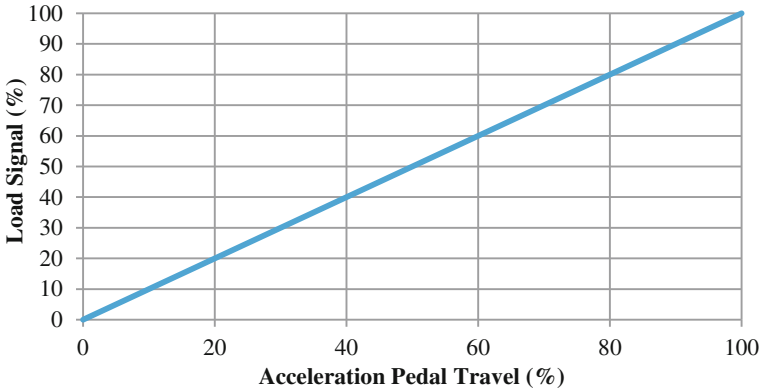


Fig. 6.13 Pedal characteristic

component group with the left mouse button, move the mouse over the required component and then click and drag the component into the vehicle model area. Put the component with release of the mouse button on the desired place.

Place the following components in the working area: Vehicle (1), IC Engine (2), Final Drive (3), Vehicle Rear Left (4), Vehicle Front Left (5), Vehicle Rear Right (6), Vehicle Front Right (7), Rear Disk Brake (8), Front Disk Brake (9), Rear Disk Brake (10), Front Disk Brake (11), E-Machine (12), Generator (13), Differential (14), Cockpit (15), ASC (16), Electrical Consumer (17), Battery H (18), E-Drive Function (19), E-Brake & M-Brake Function (20), Range Extender Function (21), Monitor (22), PID Control (23), and Constants (24).

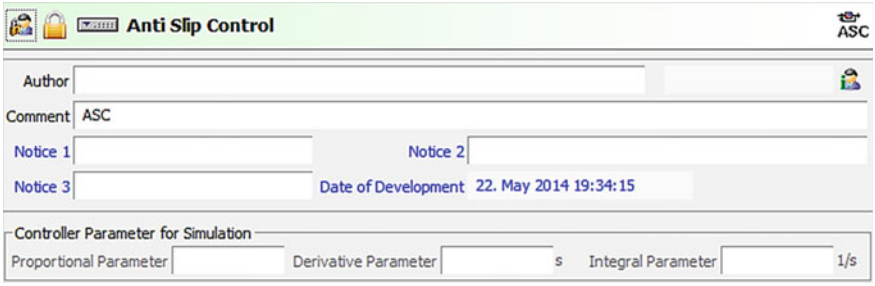


Fig. 6.14 ASC Anti-Slip Control input data specifications window

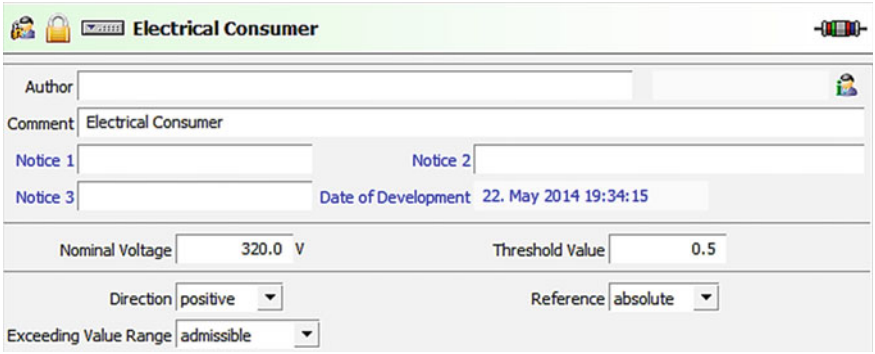


Fig. 6.15 Electrical Consumer input data specifications window

Table 6.11 Electrical Consumer input data

Name	Value	Unit
Nominal Voltage	320.0	V
Direction	Positive	–
Exceeding Value Range	Admissible	–
Threshold Value	0.500	–
Reference	Absolute	–

Arrange the components as shown in the following figure (Fig. 6.25) and connect the components as specified in the diagram [2]. All the connections in the data bus for this model are described in Table 6.20.

The **Vehicle** (1) contains general data of the vehicle (Fig. 6.26), such as nominal dimensions and weights (Table 6.21).

IC Engine (2) component contains a model for an internal combustion engine. To define component input data (Table 6.22), double click on the icon or click on it with the right mouse button and select edit to open the following window (Fig. 6.27) [1].

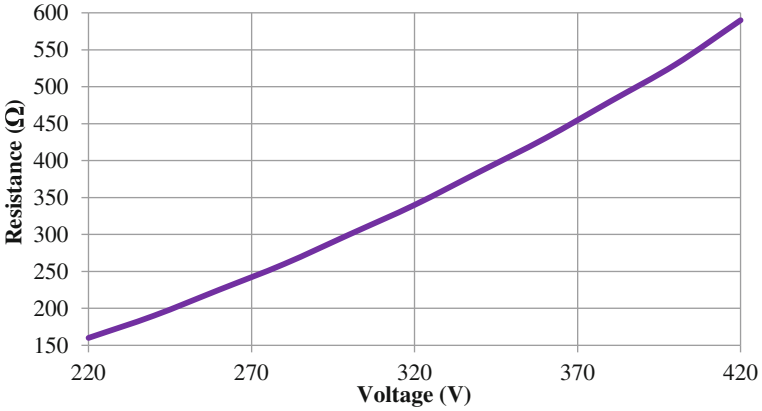


Fig. 6.16 Resistance Table

Table 6.12 Resistance Table data

Voltage (V)	Resistance (Ω)	Speed (1/min)	Torque (Nm)
220	160	340	385
240	190	360	430
260	225	380	480
280	260	400	530
300	300	420	590
320	340	–	–

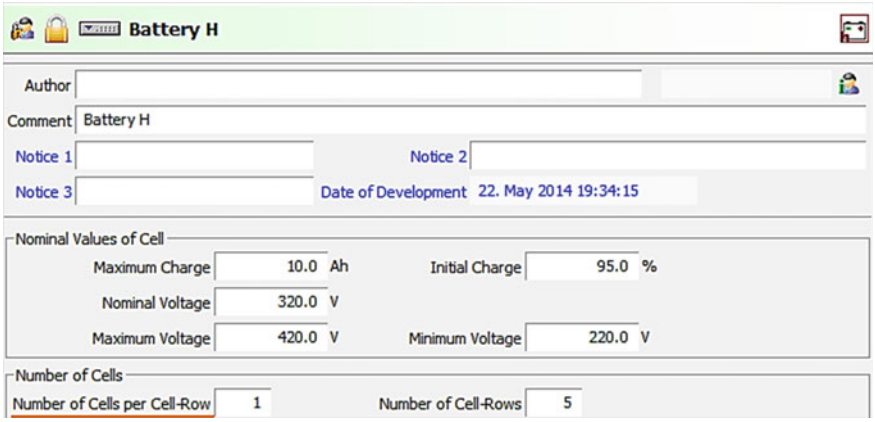


Fig. 6.17 Battery H input data specifications window

Table 6.13 Battery H input data

Name	Value	Unit
Maximum Charge	10.00	Ah
Nominal Voltage	320.0	V
Maximum Voltage	420.0	V
Initial Charge	95.00	%
Minimum Voltage	220.0	V
Number of Cells per Cell-Row	1.000	–
Number of Cell-Row	5.000	–
Operating Temperature	25.00	°C
Internal Resistance	0.800	Ω

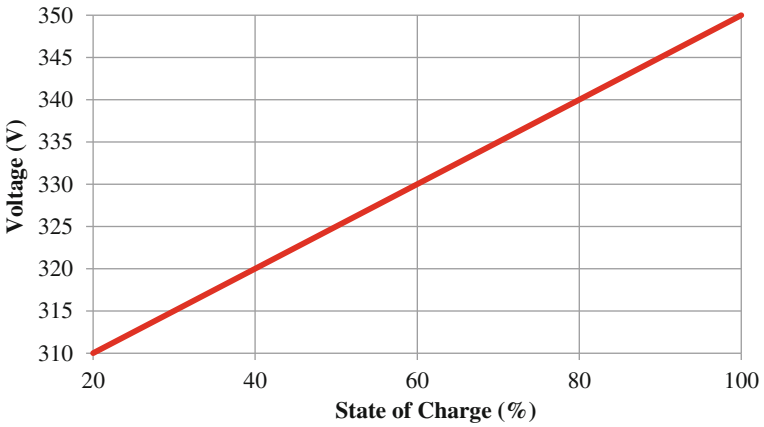


Fig. 6.18 Idle voltage charge

Table 6.14 Idle voltage—charge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
20	310	70	335
30	315	80	340
40	320	90	345
50	325	100	350
60	330	–	–

The properties window is accessed through properties button in the input data window, or from the pop up menu (Fig. 6.28).

To load engine characteristic click on the Full Load Characteristic tab (Fig. 6.29 and Table 6.23).

The Motoring Curve (Fig. 6.30) will be defined similar to the Full Load Characteristic either as power dependent on the engine speeds [2].

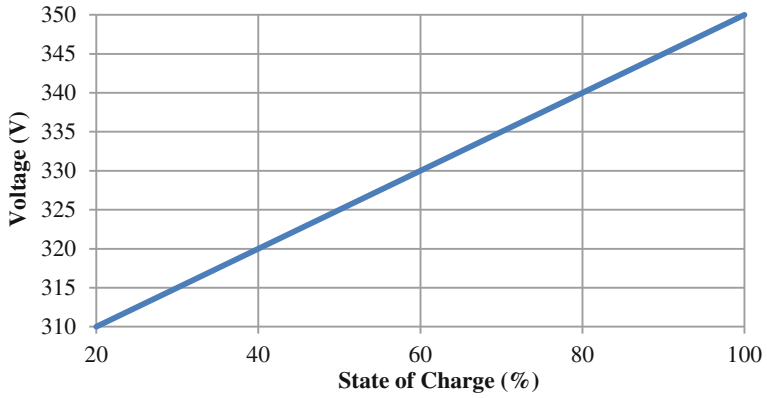


Fig. 6.19 Idle voltage discharge

Table 6.15 Idle voltage—discharge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
20	310	70	335
30	315	80	340
40	320	90	345
50	325	100	350
60	330	–	–

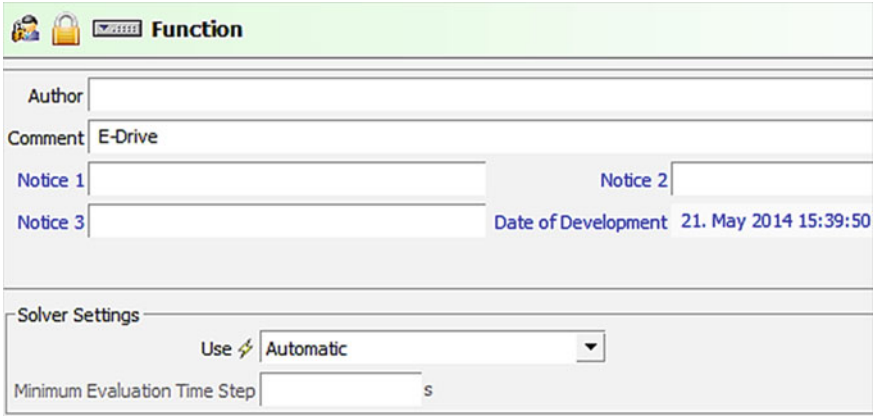


Fig. 6.20 E-Drive input data specifications window

In the Fuel Consumption Map (Fig. 6.31 and Table 6.24), the actual fuel consumption for stationary operation is listed depending on the brake mean pressure with the engine speed as parameter (a—speed (1/min), b—BMEP (bar), c—volume

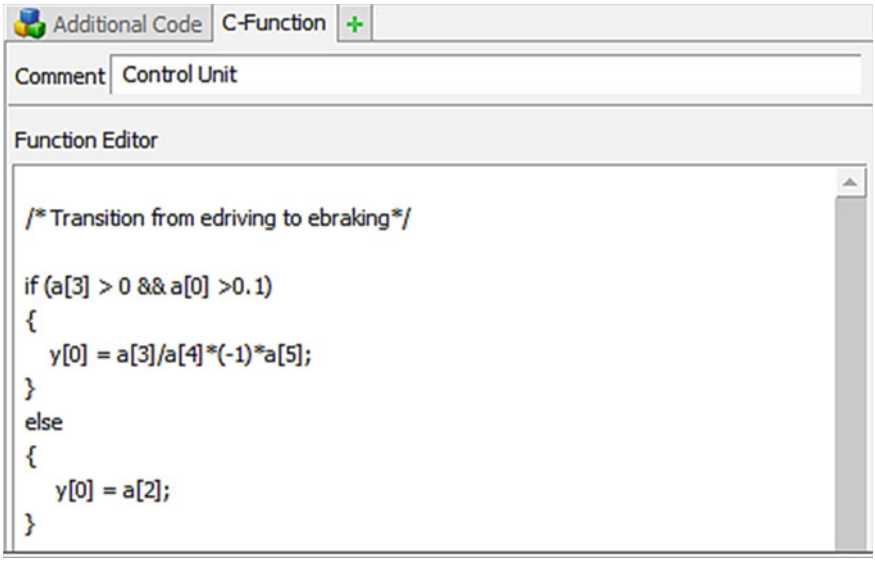


Fig. 6.21 C code function

Table 6.16 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	Vehicle Velocity	km/h	Optional	0
a[1]	Vehicle Acceleration	m/s^2	Optional	0
a[2]	Load Signal	–	Optional	0
a[3]	Brake Pressure	bar	Optional	0
a[4]	Maximum Brake Pressure	bar	Optional	0
a[5]	Brems factor	–	Optional	0
a[6]	a[6]	–	Optional	0
y[0]	Mod Load Signal	–	Optional	0

flow (l/h)). In the emission maps, the emissions for the different exhaust gases are listed dependent on the mean pressure with the engine speed as parameter (NO_x emission map—Fig. 6.32 and Table 6.25, CO emission map—Fig. 6.33 and Table 6.26, HC emission map—Fig. 6.34 and Table 6.27) [2].

Final Drive (3) or **Single Ratio Transmission** is a gear step with fixed ratio (Fig. 6.35). To define component input data, double click on the final drive icon (Table 6.28).

The **Wheel** component considers many influencing variables and their effect on the rolling state (Fig. 6.36). Information data for the four wheels is the same (Vehicle Rear Left (4), Vehicle Front Left (5), Vehicle Rear Right (6), and Vehicle Front Left (7)) [2].

Double click on the wheel and enter the following data (Table 6.29).

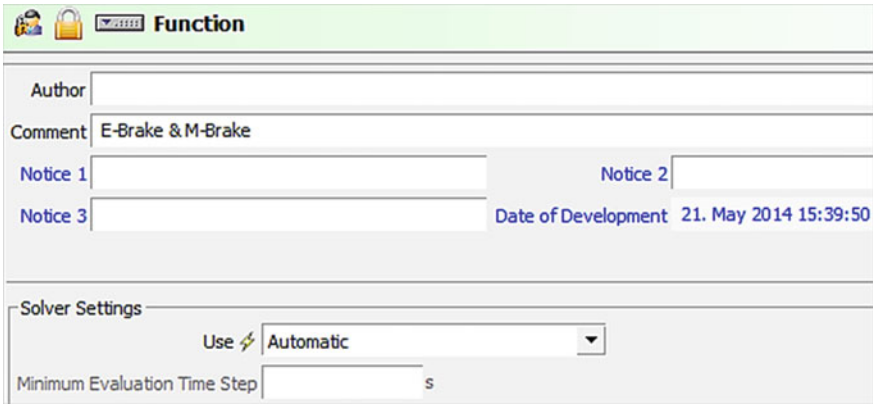


Fig. 6.22 E-Drive input data specifications window

Table 6.17 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	eDrive_Torque	Nm	Optional	0
a[1]	iFD (Ratio of Final Drive)	–	Optional	0
a[2]	iTR (Ratio of Final Transmission)	–	Optional	0
a[3]	Brake_Factor_Front	–	Optional	0
a[4]	Brake_Factor_Rear	–	Optional	0
a[5]	Brake Pressure_Driver	Pa	Optional	0
y[0]	BRK_dp_Recup	Pa	Optional	0

The **Brake** component is described by brake data and dimensions (Fig. 6.37). Input data for the two front brakes is the same and also the data for the two rear brakes is the same (Rear Disk Brake Left (8), Front Disk Brake Left (9), Rear Disk Brake Right (10), and Front Disk Brake Right (11)).

Double click on the brake icon and enter the following data (Table 6.30).

Electric Machine (12) together with the battery H the user can simulate an electric system. For this type of model, a characteristic map for the efficiency is used to calculate the loss of power [1]. Double click on the electric machine icon and enter the following data (Fig. 6.38 and Table 6.31).

The value of the voltage level should be entered at which the following characteristic maps of the machine have been measured. For each level, the corresponding voltage value must be defined and the corresponding characteristic maps (voltage for U1 = 100 V, voltage for U1 = 320 V).

The maximum mechanical (power) torque (Fig. 6.39 and Table 6.32) is defined as a function of the machines speed (a—speed (1/min), b—torque (Nm)) [2]. Efficiency map is defined dependent on speed and power (or torque) and is shown in Fig. 6.40 and Table 6.33.

Additional Code | C-Function

Comment: Conversion of edrive Torque to Brake Pressure

Function Editor

```
/*Conversion routine*/
/*Converting brake Torque into Pressure for all Brakes (Front & Rear)*/

double eBrake;

if (a[0] < 0 )
{
   eBrake = a[0]*2*a[1]*a[2]/(2*(a[3]+a[4]));
}
else
{
    eBrake = 0.;
}
/*Calculation of reduced mechanical Brake*/
/* Function to determine a maximum value*/
if ((eBrake+a[5])>0.0)
{
    y[0]= (eBrake+a[5]);
}
else
{
    y[0]= 0.0;
}
```

Fig. 6.23 C code function

Monitor

Author

Comment: Monitor

Notice 1 | Notice 2

Fig. 6.24 Monitor

Table 6.18 Description of Data Bus

Data Bus Channel	Description	Unit
Input 0	LoadSignal_Cockpit	–
Input 1	Velocity	km/h
Input 2	Torque_eDrive	Nm

Table 6.19 Description of Data Bus

Data Bus Channel	Description	Value	Unit	Data Type
Constant 0	Brake_Factor_Front	0.00012	–	Double
Constant 1	Brake_Factor_Rear	0.00008	–	Double
Constant 2	iFD (Ratio of Final Drive)	3.650	–	Double
Constant 3	iTR (Ratio of Final Transmission)	1.000	–	Double
Constant 4	Maximum Brake Pressure	50.00	bar	Double
Constant 5	Brake Factor	1.000	–	Double

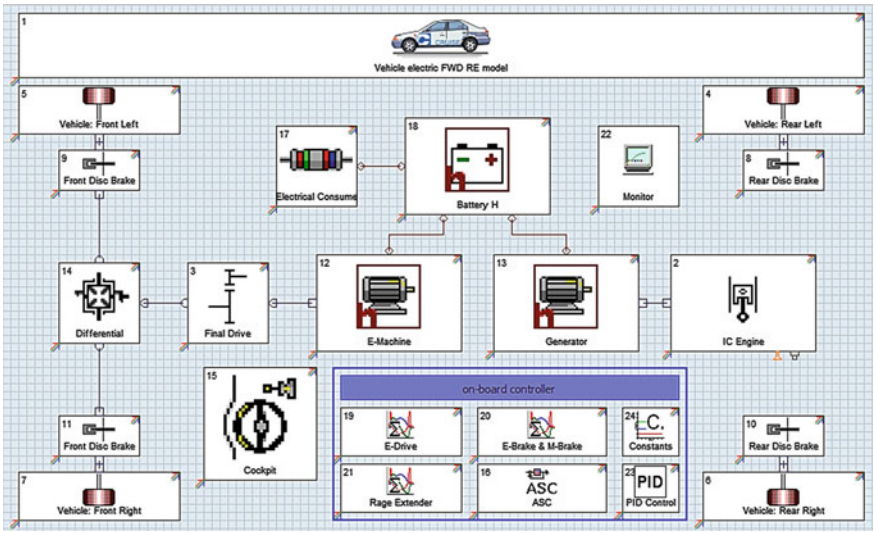


Fig. 6.25 Complete model electric FWD RE

The **Generator** (13) must supply the vehicles electrical system with a sufficient current under all operating conditions in order to ensure that the State of Charge in the engine storage device is consistently maintained at an adequate level [1]. Double click on the generator icon and enter the following data (Fig. 6.41).

The maximum mechanical (power) torque (Fig. 6.42 and Table 6.34) is defined as a function of the machines speed (a—speed (1/min), b—torque (Nm)) [2]. The efficiency map (Fig. 6.43 and Table 6.35) is defined dependent on a—speed (1/min), b—power (kW) and efficiency (%).

Differential (14) unit compensates for discrepancies in the respective rotation rates of the drive wheels (Fig. 6.44). To define component input data, double click on the differential icon and enter the following data (Table 6.36).

The Kinematic Chain Browser can be launched in the pop-up menu of a selected component. All mechanical connections starting from the selected component are shown in a tree-structure in the left side of the window (Fig. 6.45) [1].

Table 6.20 Data Bus connection

Component requires	Input information	Component delivering	Output information
ASC	Clutch Release	Cockpit	Clutch Release
	Load Signal	Cockpit	Load Signal
	Slip Signal Front Left	Wheel Front Right	Slip Signal
	Slip Signal Front Right	Wheel Front Left	Slip Signal
	Slip Signal Rear Left	Wheel Front Right	Slip Signal
	Slip Signal Rear Right	Wheel Front Left	Slip Signal
Battery H	Ambient Temperature	Cockpit	Course Ambient
	Temperature External	Cockpit	Course Ambient
Brake Rear Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Front Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Rear Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Brake Front Disk	**Brake Pressure**	E-Brake & M-Brake	BRK_dp_Recup
Cockpit	**Gear Indicator**	E-Machine	Operating Mode
	Operation Control 0	E-Machine	Operation Control
	Speed	E-Machine	Speed
E-Machine	Ambient Temperature	Cockpit	Course Ambient
	Load Signal	E-Drive	Mod Load Signal
	Temperature External	Cockpit	Course Ambient
Generator	**Load Signal**	Range Extender	Load_Signal_Gen
	Switch	Range Extender	Start_Switch_Gen
	Temperature External	Cockpit	Course Ambient
Electric Consumer	Set Value X	Battery H	Net Voltage
IC Engine	**Load Signal**	Range Extender	Load_Signal_Engine
	Start Switch	Range Extender	Start_Switch_Engine
Function E-Drive	Vehicle Velocity	Cockpit	Velocity
	Vehicle Acceleration	Cockpit	Acceleration
	Load Signal	Cockpit	Load Signal
	Brake Pressure	Cockpit	Brake Pressure
	Maxim Brake Pressure	Constants	Maxim Brake Pressure
	Bremsfactor	Constants	Brake Factor
E-Brake M-Brake	eDrive_Torque	E-Machine	Torque
	iFD	Constants	iFD
	iTR	Constants	iTR
	Brake_Factor_Front	Constants	Brake_Factor_Front
	Brake_Factor_Rear	Constants	Brake_Factor_Rear
	Brake_Pressure_Driver	Cockpit	Brake Pressure

(continued)

Table 6.20 (continued)

Component requires	Input information	Component delivering	Output information
Range Extender	SOC_Act	Battery H	State of Charge
	SOC_Min	Constants	SOC_Min
	SOC_Max	Constants	SOC_Max
	Start_Switch_CP	Cockpit	Start Switch
	Engine_Speed	IC Engine	Engine Speed
	Load_Signal_Engine	PID Control	Output Value
	Desired_Engine	Speed_Constants	Desired Engine
Monitor	LoadSignal_Cockpit	Cockpit	Load Signal
	Velocity	Cockpit	Velocity
	Torque eDrive	E-Machine	Torque
	SOC	Battery H	Start of Charge
	Engine_Speed	IC Engine	Engine Speed
PID Control	**Actual Value**	IC Engine	Engine Speed
	Desired Value	Constants	Desired Engine Speed

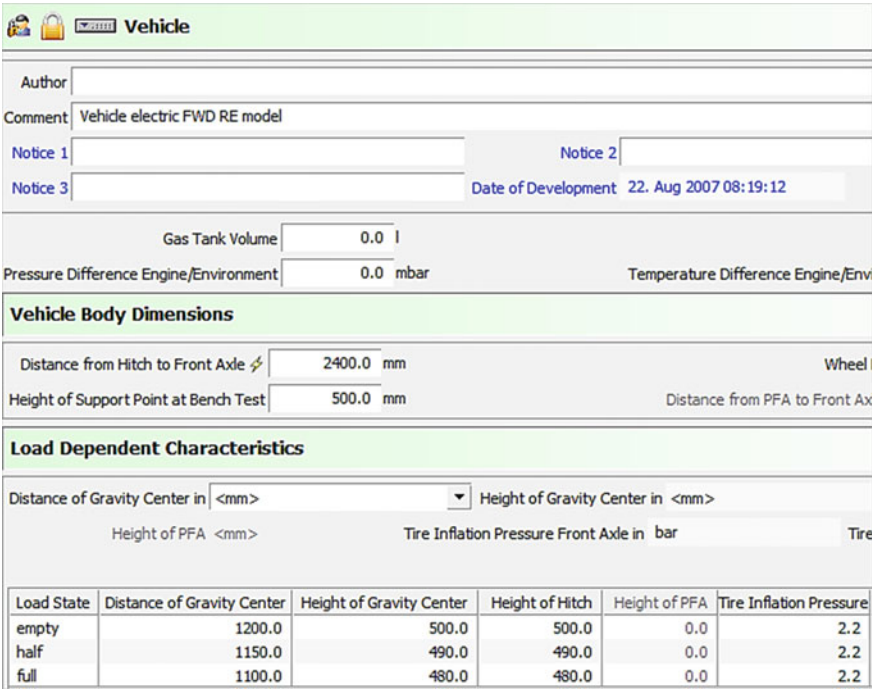


Fig. 6.26 Vehicle input data specifications window

Table 6.21 Vehicle component input data

Name	Value	Unit
Distance from Hitch to Front Axle	2400.0	mm
Height of Support Point at Bench Test	500.00	mm
Wheel Base	2400.0	mm
Distance of Gravity Center empty/half/full	1200.0/1150.0/1100.0	mm
Height of Gravity Center empty/half/full	500.0/490.0/480.0	mm
Height of Hitch empty/half/full	500.0/490.0/480.0	mm
Tire Inflation Pressure Front Axle	2.200	bar
Tire Inflation Pressure Rear Axle	2.400	bar
Curb Weight	1200.0	kg
Constant Part Resistance Function	143.0	N
Square Part Resistance Function	0.034	$N/(km/h)^2$
Gross Weight	1600.0	kg
Frontal Area	2.000	m^2

Table 6.22 IC Engine component input data

Name	Value	Unit
Engine Displacement	2000.0	cm^3
Engine Working Temperature	90.00	°C
Number of Cylinders	4.000	–
Number of Strokes	4.000	–
Idle Speed	800.0	1/min
Maximum Speed	6000.0	1/min
Inertia Moment	0.150	kg m^2
Response Time	0.100	s
Engine Type	Gasoline	–
Heating Value for Gasoline	44200.0	kJ/kg
Fuel Density	0.760	kg/l

The **Cockpit** (15) links the driver and the vehicle. In this component, connections are only made via the Data Bus (Fig. 6.46). The pedal positions are transferred into corresponding indicators via the pedal characteristics (Table 6.37).

To define the input data, click on the acceleration pedal characteristic (a—acceleration pedal travel (%), b—load signal (%)), clutch pedal characteristic (a—clutch pedal travel (%), b—clutch release (%)), and brake pedal characteristic (a—specific brake pedal force (%), b—brake pressure (bar)) tabs and enter the following data for all (Fig. 6.47) [2].

The **ASC Anti-Slip Control** (16) checks the force transmission factor of all connected wheels (Fig. 6.48). The Anti-Slip Control is only active when a model is calculated quasi-stationary in combination with special drivetrain configurations and does not require data entry.

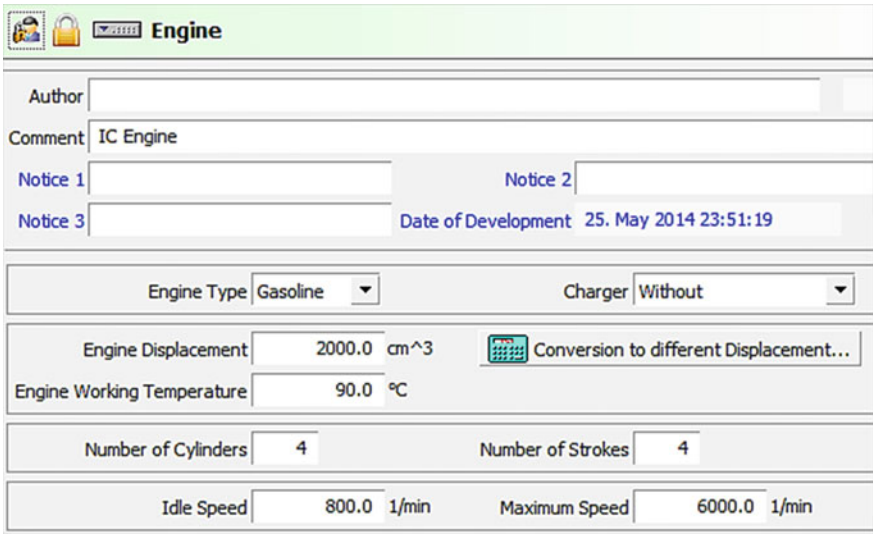


Fig. 6.27 IC Engine input data specifications window

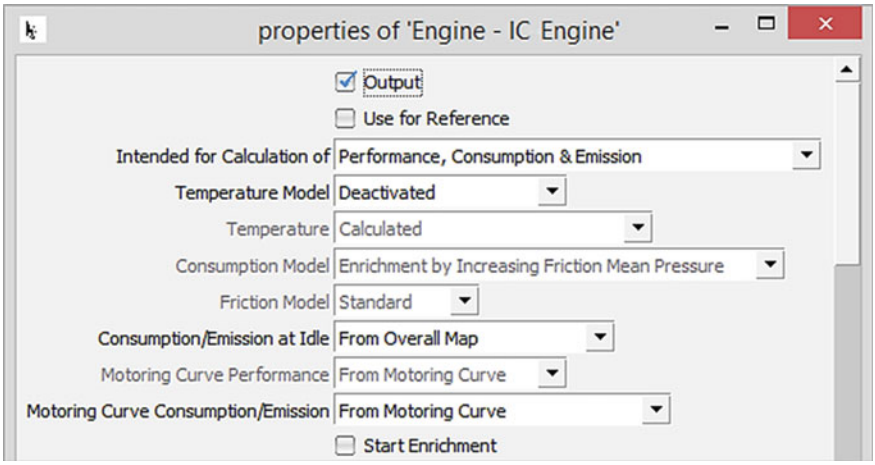


Fig. 6.28 Properties of IC Engine

The **Electrical Consumer** (17) is represented as ohmic resistors in the onboard network (Fig. 6.49). They represent an electric current loss. Double click on the electrical consumer icon and enter the data (Table 6.38).

The electrical consumer can be described as resistance depending on input value a—voltage (V) and b—resistance (Ω) in Resistance Table (Fig. 6.50).

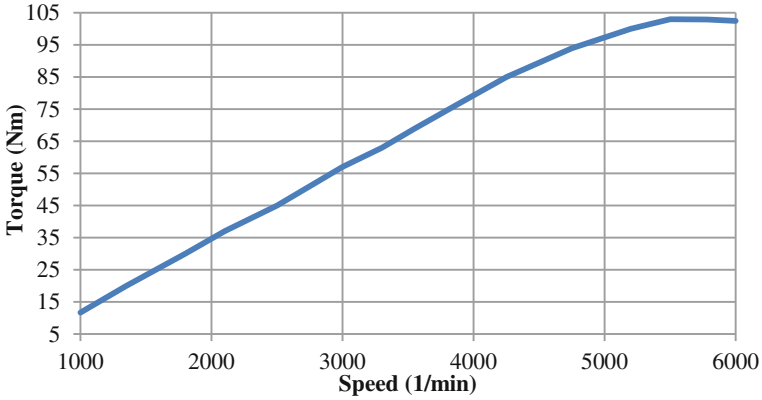


Fig. 6.29 Full Load Characteristic

Table 6.23 Full Load Characteristic data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
800	7	3900	77
1350	20	4250	85
1800	30	4750	94
2100	37	5200	100
2500	45	5500	103
3000	57	5780	103
3300	63	6000	102
3550	69	–	–

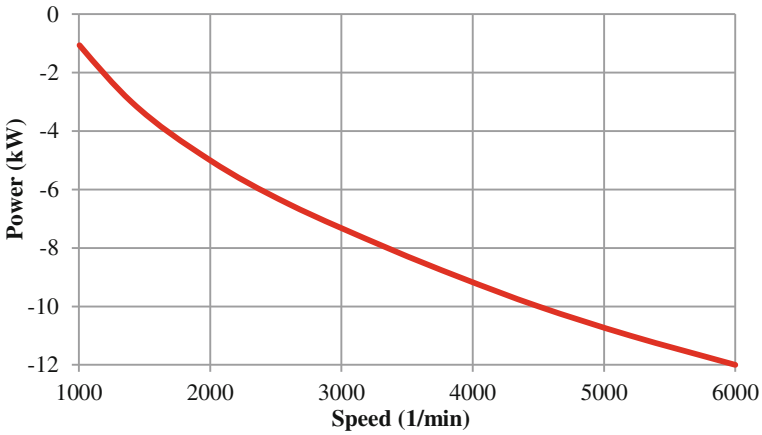


Fig. 6.30 Motoring Curve

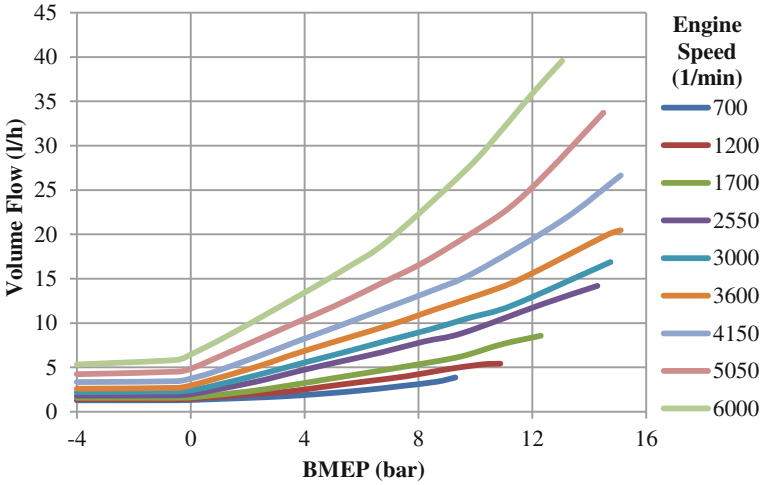


Fig. 6.31 Fuel Consumption Map

Table 6.24 Fuel Consumption Map data

(a)											
700	(b)	−4.0	−0.5	0.0	1.60	3.16	4.55	5.95	7.32	8.63	9.3
	(c)	1.29	1.30	1.33	1.52	1.72	2.01	2.39	2.87	3.38	3.86
1200	(b)	−4.0	−0.5	0.0	1.82	3.32	4.73	6.17	7.59	8.90	10.9
	(c)	1.41	1.42	1.45	1.90	2.24	2.84	3.43	4.01	4.74	5.42
1700	(b)	−4.0	−0.5	0.0	2.06	3.54	4.89	7.83	9.48	10.9	12.3
	(c)	1.57	1.58	1.61	2.30	3.00	3.72	5.26	6.22	7.61	8.57
2550	(b)	−4.0	−0.5	0.0	2.30	3.80	5.25	8.21	9.55	12.4	14.3
	(c)	1.82	1.86	1.97	3.39	4.59	5.65	7.93	8.87	12.1	14.2
3000	(b)	−4.0	−0.5	0.0	2.42	3.97	5.49	8.41	9.81	11.3	14.7
	(c)	2.20	2.29	2.42	4.20	5.53	6.78	9.28	10.6	11.9	16.8
3600	(b)	−4.0	−0.5	0.0	2.41	3.97	8.59	10.3	11.6	14.7	15.1
	(c)	2.60	2.69	2.96	5.16	6.83	11.5	13.4	15.0	20.0	20.5
4150	(b)	−4.0	−0.5	0.0	2.31	3.82	5.34	8.53	9.99	13.1	15.2
	(c)	3.35	3.44	3.74	6.18	8.04	9.83	13.7	15.7	21.6	26.6
5050	(b)	−4.0	−0.5	0.0	3.62	5.10	6.63	9.77	11.2	12.5	14.5
	(c)	4.24	4.52	4.84	9.93	11.0	14.4	19.9	22.8	27.0	33.7
6000	(b)	−4.0	−0.5	0.0	2.76	4.18	5.53	9.72	10.9	12.1	13.0
	(c)	5.33	5.85	6.45	11.2	13.7	16.3	27.4	31.6	36.0	39.6

The **Battery H** (18) component is used for simulating electrical vehicles (Fig. 6.51). Double click on the battery H icon and enter the following data (Table 6.39) [2].

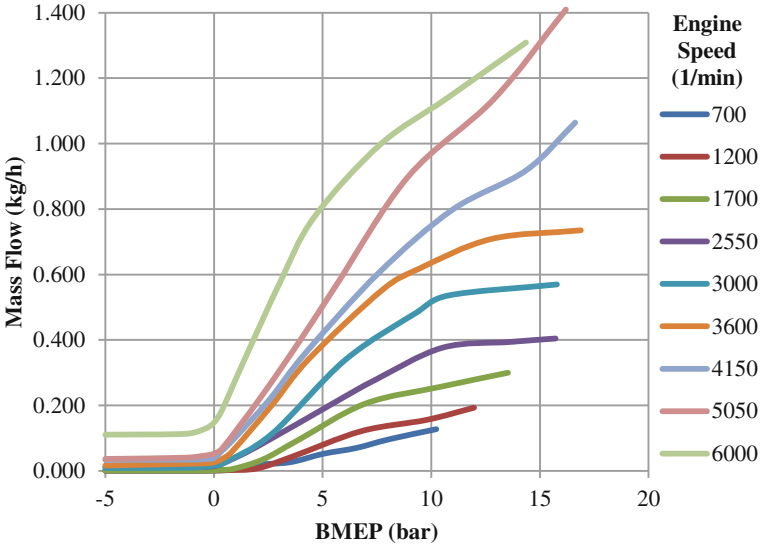


Fig. 6.32 NO_x emission map

Table 6.25 NO_x emission map data

(a)											
700	(b)	−5	−1	0	1	2	3	5	7	8	10
	(c)	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.07	0.10	0.13
1200	(b)	−5	0	0	0	1	2	4	7	10	12
	(c)	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.12	0.16	0.19
1700	(b)	−5	0	0	0	1	2	4	7	10	14
	(c)	0.00	0.00	0.00	0.00	0.01	0.04	0.10	0.21	0.26	0.30
2550	(b)	−5	0	0	0	2	6	7	11	14	16
	(c)	0.01	0.01	0.02	0.02	0.08	0.22	0.28	0.38	0.39	0.41
3000	(b)	−5	−1	0	0	0	3	6	9	11	16
	(c)	0.01	0.01	0.01	0.02	0.02	0.11	0.34	0.48	0.54	0.57
3600	(b)	−5	0	0	1	3	4	8	9	13	17
	(c)	0.02	0.02	0.03	0.06	0.20	0.34	0.55	0.62	0.71	0.74
4150	(b)	−5	−1	0	1	3	4	8	11	14	17
	(c)	0.03	0.03	0.04	0.09	0.22	0.36	0.61	0.80	0.92	1.06
5050	(b)	−5	−1	0	0	2	4	6	9	13	16
	(c)	0.04	0.04	0.05	0.07	0.23	0.40	0.57	0.90	1.14	1.41
6000	(b)	−5	−1	0	0	1	3	5	8	11	14
	(c)	0.11	0.13	0.15	0.18	0.33	0.58	0.77	0.99	1.14	1.31

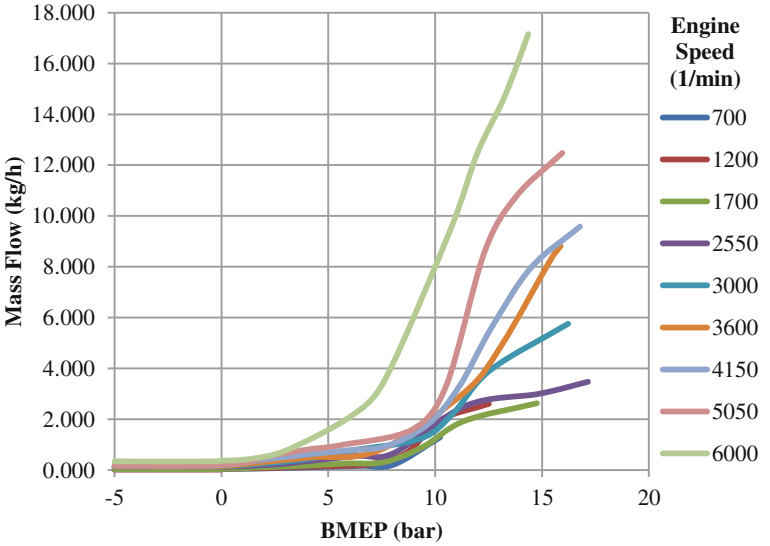


Fig. 6.33 CO emission map

Table 6.26 CO emission map data

(a)											
700	(b)	−5	−1	0	2	3	5	7	8	10	–
	(c)	0.04	0.04	0.05	0.07	0.10	0.14	0.17	0.22	1.30	–
1200	(b)	−5	−1	0	2	4	5	7	9	10	13
	(c)	0.02	0.02	0.06	0.08	0.13	0.17	0.25	0.70	1.97	2.61
1700	(b)	−5	−1	0	1	2	6	8	9	11	15
	(c)	0.04	0.04	0.05	0.06	0.13	0.27	0.32	0.90	1.94	2.63
2550	(b)	−5	−1	0	1	3	6	8	11	15	17
	(c)	0.12	0.12	0.13	0.15	0.23	0.56	0.67	2.54	3.01	3.50
3000	(b)	−5	0	1	3	4	6	9	11	13	16
	(c)	0.12	0.15	0.19	0.32	0.49	0.77	1.23	2.22	3.95	5.76
3600	(b)	−5	−1	0	1	3	7	11	13	15	16
	(c)	0.13	0.14	0.16	0.21	0.37	0.79	3.03	4.89	8.30	8.82
4150	(b)	−5	−1	0	1	6	10	11	13	14	17
	(c)	0.17	0.18	0.20	0.26	0.78	1.81	3.29	5.59	7.98	9.58
5050	(b)	−5	−1	0	1	4	9	11	12	14	16
	(c)	0.20	0.20	0.23	0.33	0.81	1.60	3.33	8.58	10.8	12.5
6000	(b)	−5	−1	0	1	6	8	11	12	13	14
	(c)	0.35	0.35	0.37	0.44	2.14	3.53	9.42	12.5	14.7	17.2

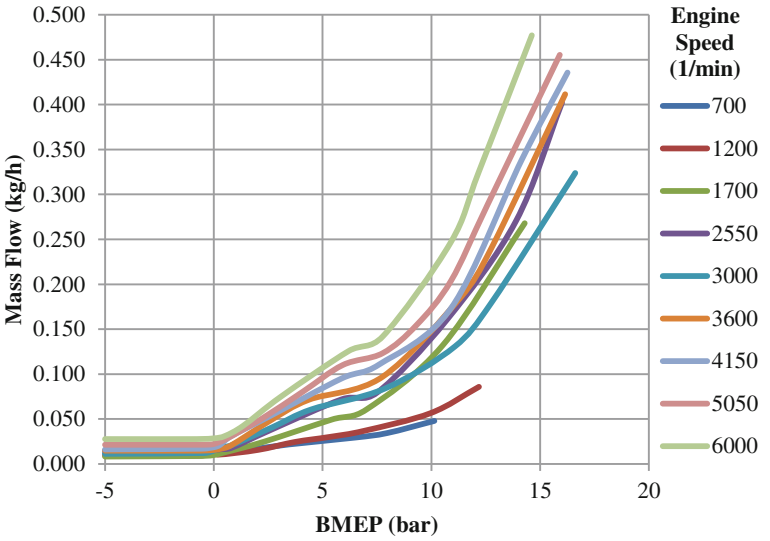


Fig. 6.34 HC emission map

Table 6.27 HC emission map data

(a)											
700	(b)	−5	−1	0	1	2	3	6	8	10	−
	(c)	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.05	
1200	(b)	−5	−1	0	0	2	4	5	7	10	12
	(c)	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.06	0.09
1700	(b)	−5	−1	0	0	2	5	7	11	14	−
	(c)	0.01	0.01	0.01	0.01	0.03	0.05	0.06	0.13	0.27	−
2550	(b)	−5	−1	0	1	3	6	8	11	14	16
	(c)	0.02	0.02	0.02	0.02	0.04	0.07	0.08	0.16	0.27	0.40
3000	(b)	−5	0	0	1	3	4	8	11	13	17
	(c)	0.01	0.02	0.02	0.02	0.04	0.06	0.08	0.13	0.18	0.32
3600	(b)	−5	−1	0	1	3	4	8	11	13	16
	(c)	0.02	0.02	0.02	0.02	0.05	0.07	0.10	0.19	0.24	0.41
4150	(b)	−5	−1	0	1	3	6	8	11	14	16
	(c)	0.02	0.02	0.02	0.03	0.05	0.10	0.11	0.17	0.34	0.44
5050	(b)	−5	0	1	2	6	8	9	11	13	16
	(c)	0.02	0.02	0.03	0.05	0.11	0.12	0.16	0.20	0.29	0.46
6000	(b)	−5	−1	0	1	3	6	8	11	12	15
	(c)	0.03	0.03	0.03	0.04	0.08	0.13	0.14	0.25	0.33	0.48

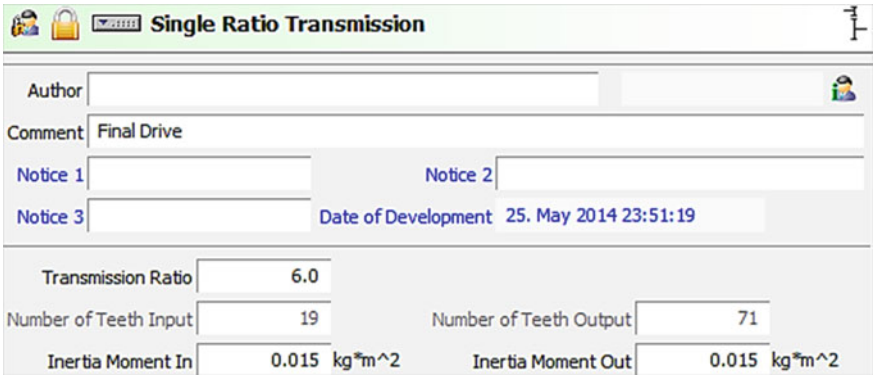


Fig. 6.35 Final Drive input data specifications window

Table 6.28 Final Drive input data

Name	Value	Unit
Transmission Ratio	6.000	–
Inertia Moment In/Out	0.015/0.015	kg m^2
Efficiency	0.950	–

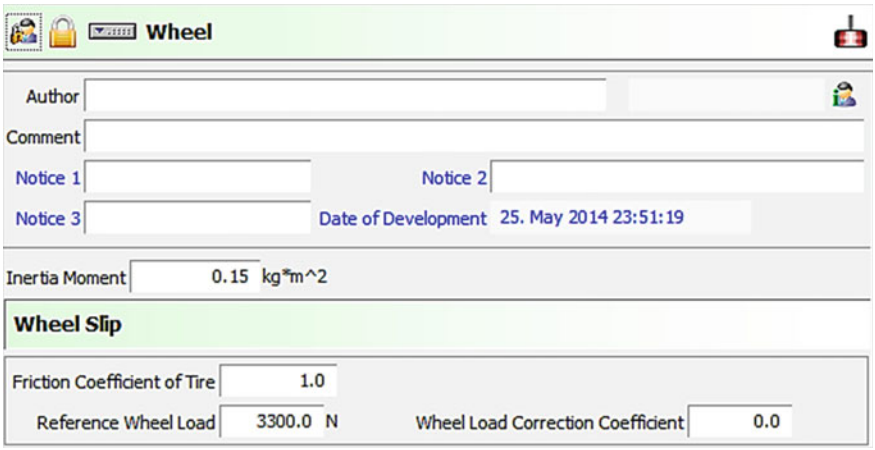


Fig. 6.36 Wheels input data specifications window

The idle voltage—charge (b) is the idle voltage of one cell in charge mode. There is no electrical consumer; it is a function of the State of Charge SOC (a) (Fig. 6.52 and Table 6.40). The idle voltage—discharge (b) of one cell is the voltage without an electrical consumer, there is no flow of current, and it is a function of the SOC (a) (Fig. 6.53 and Table 6.41) [1].

Table 6.29 Wheels input data

Name	Value	Unit
Wheel Inertia Moment	0.150	kg m^2
Friction Coefficient of Tire	1.000	–
Reference Wheel Load	3300.00	N
Wheel Load Correction Coefficient	0.000	–
Static Rolling Radius	290.0	mm
Circumference	1822.12	mm
Dynamic Rolling Radius	300.0	mm
Circumference	1884.96	mm
Friction Coefficient of Road	1.050	–
Slip at Maximum Traction	7.000	%

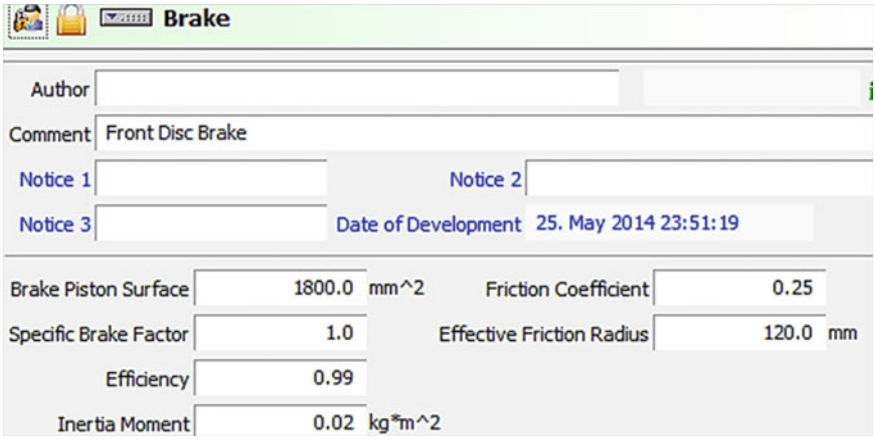


Fig. 6.37 Brake input data specifications window

Table 6.30 Brakes input data

Name	Value	Value	Value	Value	Unit
Brake	Front Right	Rear Right	Front Left	Rear Left	–
Piston Surface	1800.0	1500.0	1800.0	1500.0	mm^2
Specific Factor	1.000	1.000	1.000	1.000	–
Efficiency	0.990	0.990	0.990	0.990	–
Inertia Moment	0.015	0.015	0.015	0.015	kg m^2
Friction Coefficient	0.250	0.250	0.250	0.250	–
Friction Radius	120.0	100.0	120.0	100.0	mm

E-Drive (19) component is a function that can be used for calculations (with user-defined functions) (Fig. 6.54). To define component input data, double click on the C code icon and enter the following data for function (Fig. 6.55), and for description of Data Bus (Table 6.42) [1].

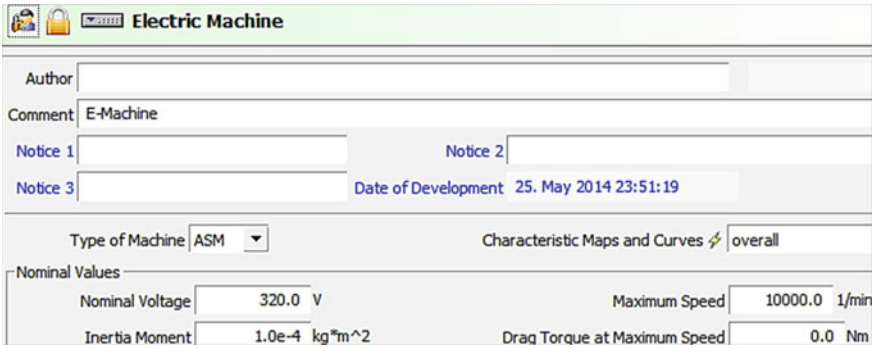


Fig. 6.38 E-Machine input data specifications window

Table 6.31 E-Machine input data

Name	Value	Unit
Type of Machine	ASM	–
Characteristic Maps and Curves	Overall	–
Nominal Voltage	320	V
Inertia Moment	1.0e−4	kg m^2
Maximum Speed	10000	1/min
Drag Torque at Maximum Speed	0	Nm
Initial Temperature	20	°C
U1 Voltage	100	V
U2 Voltage	320	V

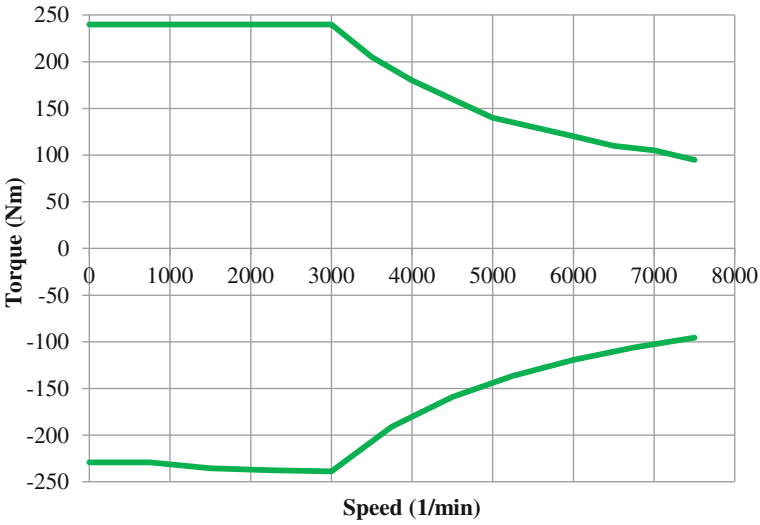


Fig. 6.39 Maximum mechanical torque

Table 6.32 Maximum mechanical torque data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
0	240	4500	160	1500	−236
500	240	5000	140	2250	−238
1000	240	5500	130	3000	−239
1500	240	6000	120	3750	−191
2000	240	6500	110	4500	−159
2500	240	7000	105	5250	−136
3000	240	7500	95	6000	−119
3500	205	1	−229	6750	−106
4000	180	750	−229	7500	−95

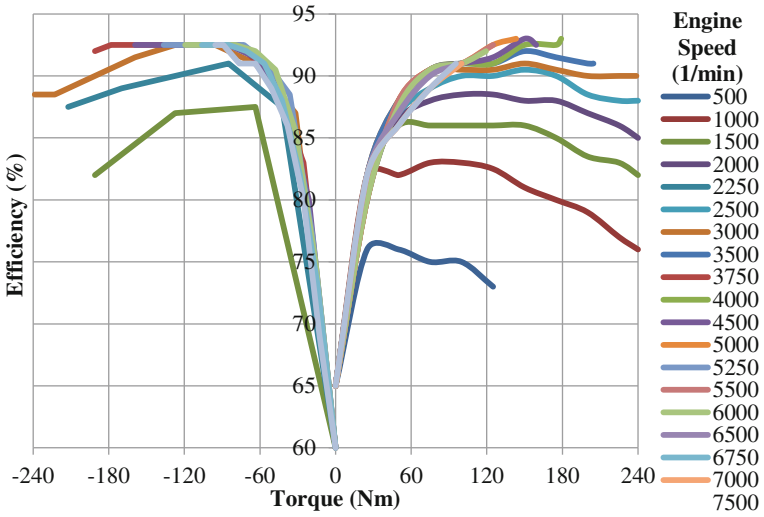


Fig. 6.40 Efficiency map

E-Brake & M-Brake (20) component is a function can be used for calculating with user-defined functions used to conversion of e-drive torque to brake pressure (Fig. 6.56). To define component input data, double click on the C code icon and enter the data for function (Fig. 6.57), and for Data Bus (Table 6.43) [1].

Range Extender (21) component is a function can be used for calculating with user-defined functions used to range extender control (Fig. 6.58). To define component input data, double click on the C code icon and enter the following data for function (Fig. 6.59), and for Data Bus (Table 6.44) [1].

The **Monitor** element (22) can be introduced, if the calculation run must be detected (Fig. 6.60). Click on the description of Data Bus tab and open the following dialog. To select a Data Bus channel, click to access at the available list [1]. Enter the text for the description and then click on to select the unit (Table 6.45).

Table 6.33 Efficiency curve data

(a)												
500	(b)	0	25	50	75	100	125	–	–	–	–	–
	(c)	65	76	76	75	72	73	–	–	–	–	–
1000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	82	83	83	83	81	80	79	77	76
1500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	86	86	86	86	86	85	84	83	82
2000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	87	88	89	89	88	88	87	86	85
2500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	87	89	90	90	91	90	89	88	88
3000	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	82	88	91	91	91	91	91	90	90	90
3500	(b)	0	25	50	75	100	125	150	175	200	225	–
	(c)	65	82	88	91	91	91	92	92	91	91	–
4000	(b)	0	25	50	75	100	125	150	175	200	–	–
	(c)	65	80	88	91	91	91	93	93	93	–	–
4500	(b)	0	25	50	75	100	125	150	175	200	225	240
	(c)	65	80	88	91	91	92	93	93	93	93	93
5000	(b)	0	25	50	75	100	125	150	–	–	–	–
	(c)	65	80	88	91	91	93	93	–	–	–	–
5500	(b)	0	25	50	75	100	125	–	–	–	–	–
	(c)	65	80	88	91	91	93	–	–	–	–	–
6000	(b)	0	25	50	75	100	125	–	–	–	–	–
	(c)	65	80	88	91	91	92	–	–	–	–	–
6500	(b)	0	25	50	75	100	–	–	–	–	–	–
	(c)	65	82	87	90	91	–	–	–	–	–	–
7500	(b)	0	25	50	75	100	–	–	–	–	–	–
	(c)	65	82	86	89	91	–	–	–	–	–	–

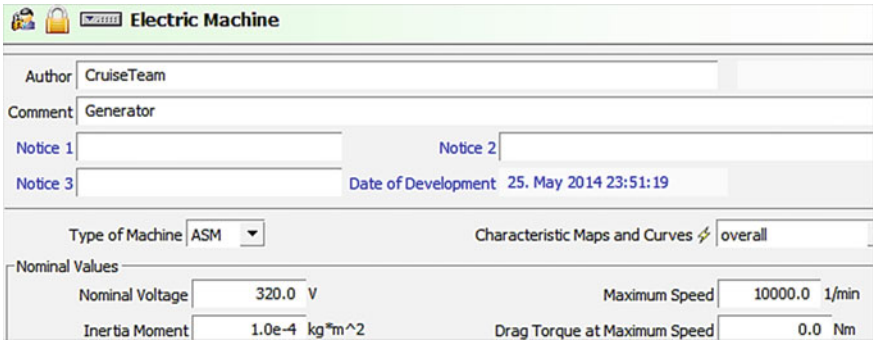


Fig. 6.41 Generator input data specifications window

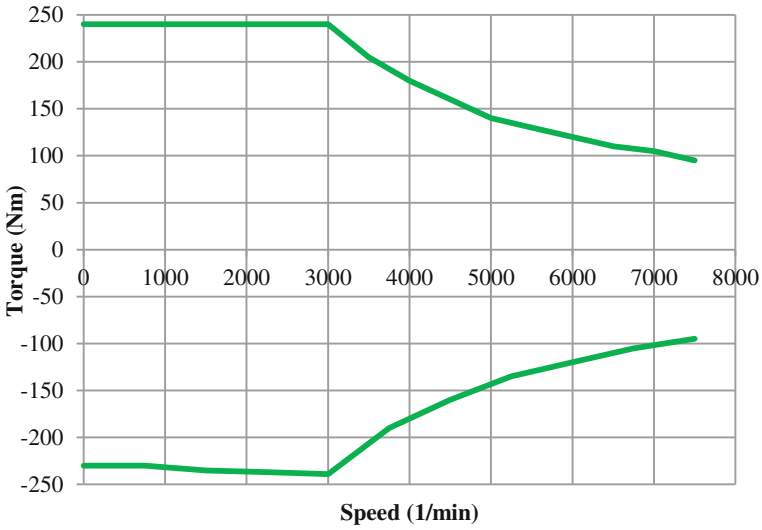


Fig. 6.42 Maximum mechanical torque

Table 6.34 Maximum mechanical torque data

Speed (1/min)	Torque (Nm)	Speed (1/min)	Torque (Nm)
1	240	1	−230
500	240	750	−230
1000	240	1500	−235
1500	240	2250	−237
2000	240	3000	−239
2500	240	3750	−190
3000	240	4500	−160
3500	205	5250	−135
4000	180	6000	−120
4500	160	6750	−105
5000	140	7500	−95
5500	130	–	–
6000	120	–	–
6500	110	–	–
7000	105	–	–
7500	95	–	–

PID Control (23) may be used to build up more powerful control subsystems in AVL CRUISE, combined with other signal processing components (Fig. 6.61). Double click on the PID control icon and enter the data (Table 6.46).

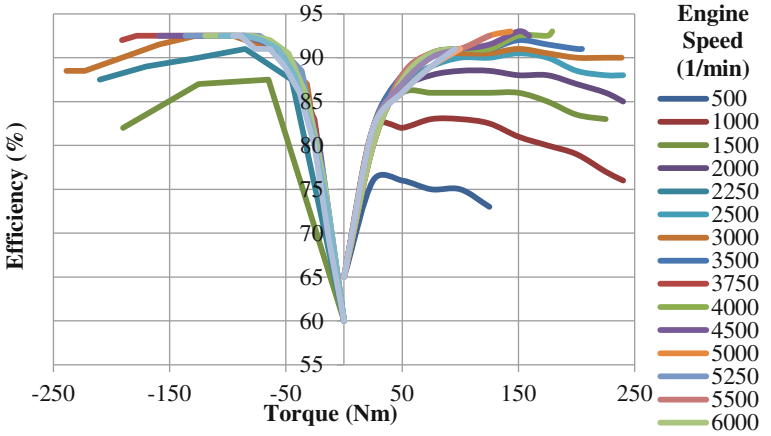


Fig. 6.43 Efficiency map

Table 6.35 Efficiency curve data

(a)											
500	0	25	50	75	100	125	150	175	200	225	240
	65	76	76	75	75	73	–	–	–	–	–
1000	0	25	50	75	100	125	150	175	200	225	240
	65	82	82	83	83	83	81	80	79	77	76
1500	0	25	50	75	100	125	150	175	200	225	240
	65	82	86	86	86	86	86	85	84	83	–
2000	0	25	50	75	100	125	150	175	200	225	240
	65	82	87	88	89	89	88	88	87	86	86
2500	0	25	50	75	100	125	150	175	200	225	240
	65	82	87	89	90	90	91	90	89	88	88
3000	0	25	50	75	100	125	150	175	200	225	240
	65	82	88	91	91	91	91	91	90	90	90
3500	0	25	50	75	100	125	150	175	200	225	240
	65	82	88	91	91	91	92	92	91	91	–
4000	0	25	50	75	100	125	150	175	200	225	240
	65	80	88	91	95	91	93	93	93	–	–
4500	0	25	50	75	100	125	150	175	200	225	240
	65	80	88	91	91	92	93	93	–	–	–
5000	0	25	50	75	100	125	150	175	200	225	240
	65	80	88	91	91	93	93	–	–	–	–
5500	0	25	50	75	100	125	150	175	200	225	240
	65	80	88	91	91	93	93	–	–	–	–
6000	0	25	50	75	100	125	150	175	200	225	240
	65	80	88	91	91	–	–	–	–	–	–

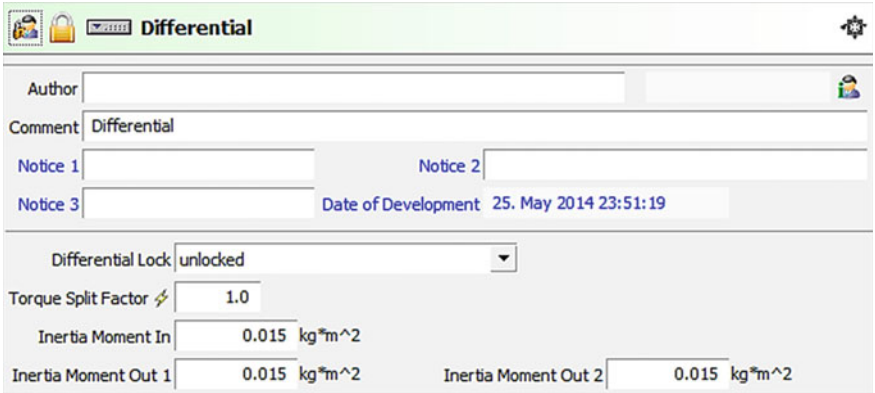


Fig. 6.44 Differential input data specifications window

Table 6.36 Differential input data

Name	Value	Unit
Differential Lock	Unlocked	–
Torque Split Factor	1.000	–
Inertia Moment In	0.015	kg m^2
Inertia Moment Out1	0.015	kg m^2
Inertia Moment Out2	0.015	kg m^2
Stationary Efficiency	0.950	–

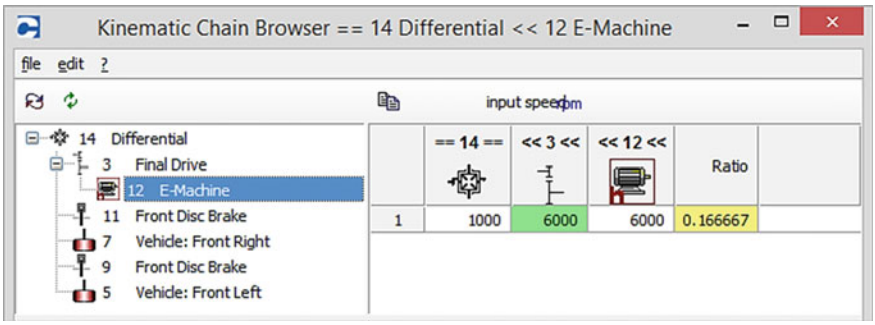


Fig. 6.45 Kinematic Chain Browser

Constants (24) component enables the user to define up to 99 constant values which can be used by other components through the Data Bus (Fig. 6.62). The values can be of type integer, double or string (Table 6.47) [1].

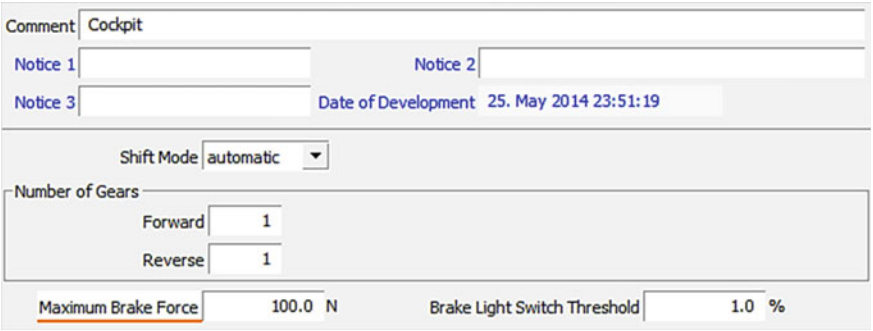


Fig. 6.46 Cockpit input data specifications window

Table 6.37 Cockpit input data

Name	Value	Unit
Shift Mode	Manual	–
Number of Gears Forward	1.000	–
Number of Gears Back	1.000	–
Maximum Brake Force	100.0	N
Brake Light Switch Threshold	1.000	%
Number of Retarder Steps	0.000	–

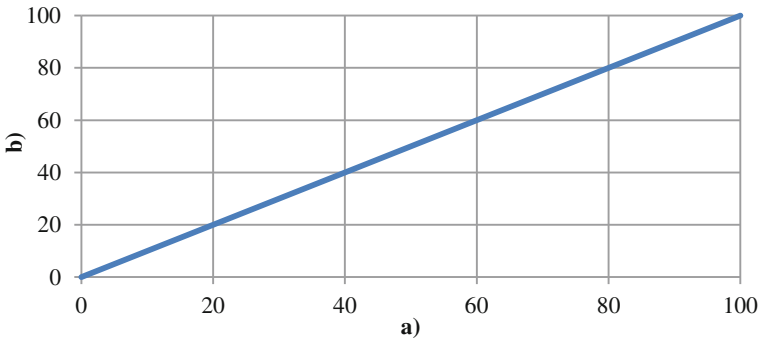


Fig. 6.47 Pedal characteristic

6.2 Run Simulation

6.2.1 Result Manager

To run a simulation for each model, there are five different options for calculation [1]:

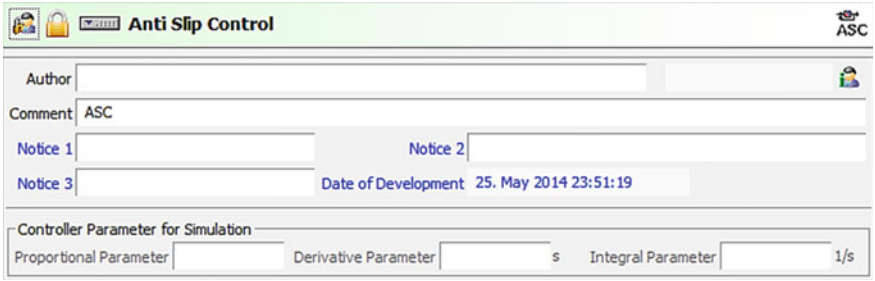


Fig. 6.48 ASC input data specifications window



Fig. 6.49 Electrical Consumer input data specifications window

Table 6.38 Electrical Consumer input data

Name	Value	Unit
Nominal Voltage	320.0	V
Direction	Positive	–
Exceeding Value Range	Admissible	–
Threshold Value	0.500	–
Reference	Absolute	–

- Single Calculation is a regular calculation with the input data supplied in the components. Output of result defines which components result will be written and available in the Result Manager.
- Matrix Calculation is used for multiple calculations and to evaluate the effect of varying the values of input parameters on vehicle performance, consumption, and emissions. The results can be viewed for each varied calculation.
- Component Variation is used for multiple calculations and the calculation consists of subcalculations in which components are replaced by components of the same type. The results can be viewed in the Result Manager.

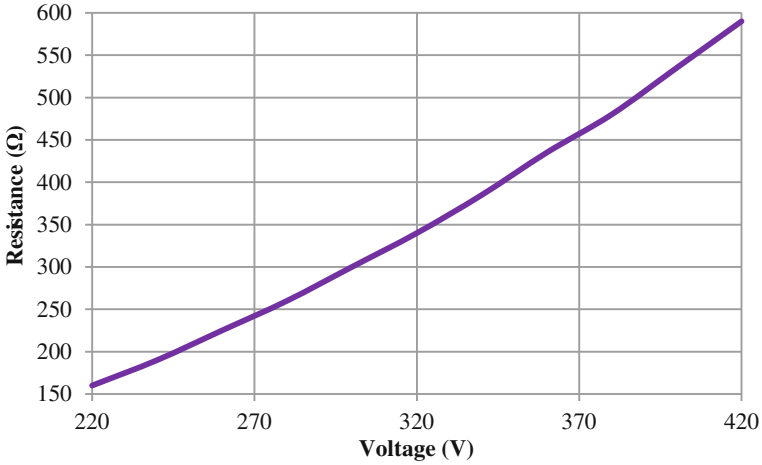


Fig. 6.50 Resistance Table

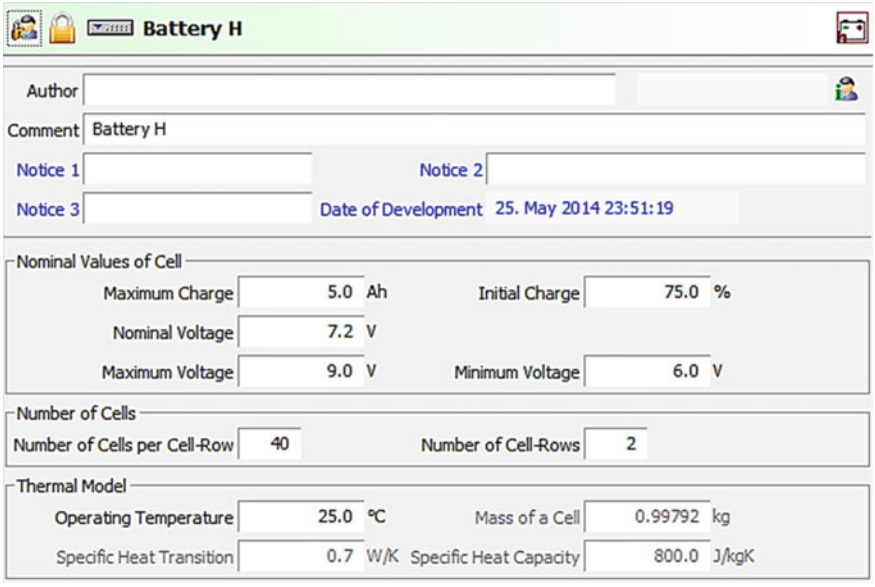


Fig. 6.51 Battery H input data specifications window

- System Variation is used for multiple calculations from a list of all the model's systems. The results can be viewed similar to Component Variation.
- Batch Calculation is used for calculations series of different projects, either Single Calculation, Matrix Calculation with DoE option, and Component Variation with DoE option.

Table 6.39 Battery H input data

Name	Value	Unit
Maximum Charge	5.000	Ah
Nominal Voltage	7.200	V
Maximum Voltage	9.000	V
Initial Charge	75.00	%
Minimum Voltage	6.000	V
Number of Cells per Cell-Row	40.00	–
Number of Cell-Row	2.000	–
Operating Temperature	25.00	°C
Internal Resistance	0.200	Ω

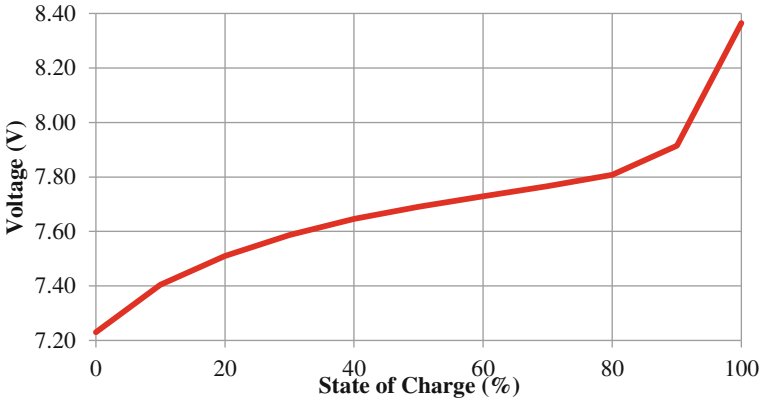


Fig. 6.52 Idle voltage charge

Table 6.40 Idle voltage—charge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	7.23	60	7.73
10	7.40	70	7.77
20	7.51	80	7.81
30	7.59	90	7.91
40	7.65	100	8.36
50	7.69	–	–

To run the calculation in the Desk Area, click on Calculation Center or click on AVL blue button in the upper right corner (Fig. 6.63). Click on to "Start Calculation" button to running the simulation.

After the simulations were complete, click on the Result Manager in the Navigation Frame (Fig. 6.64) and expand the task of which the results should be viewed. The selected object is shown in the right section of the window.

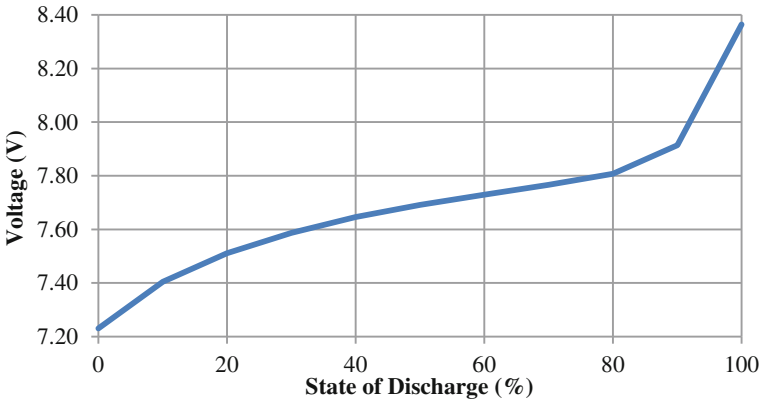


Fig. 6.53 Idle voltage discharge

Table 6.41 Idle voltage—discharge data

State of Charge (%)	Voltage (V)	State of Charge (%)	Voltage (V)
0	7.23	60	7.73
10	7.40	70	7.77
20	7.51	80	7.81
30	7.59	90	7.91
40	7.65	100	8.36
50	7.69	–	–

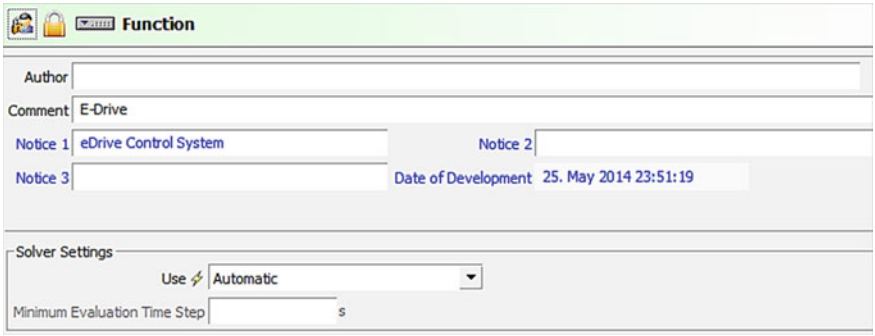


Fig. 6.54 E-Drive input data specifications window

Project information can be viewed in the main window by selecting info in the tree structure or by double clicking info in the right window. The window shows general information: project name, author, vehicle model, drivetrain model, date and state (regarding errors), then the tree structure of the Folder with defined Calculation Tasks (different status for run or not run is shown using blue/grey color). The picture of the Vehicle Model is also displayed.

```
/* Transition from edriving to ebraking*/
/*Checking whether the Driver applies the Brake pedal. This information can be
directly taken from Cockpit: if the Brake Pressure is greater than Zero then there is
a braking action additional the vehicle should still be on the move
*/
if (a[3] > 0 && a[0] >0.1)
{
/*In this case the Brake pressure should be converted into Ratio of the maximum
Brake Pressure. Additional a brake Factor can be also used to scale this ratio ac-
cording to the size of E-Motor in order to get suitable load to the E-Drive.
a[0] : Vehicle Velocity;
a[1]: Vehicle Acceleration;
a[2]: Load Signal;
a[3]: Brake Pressure;
a[4]: Maximum Brake Pressure;
a[5]:Brake factor.
*/
   y[0] = a[3]/a[4]*(-1)*a[5];
}
else
{
/*If there isn't any brake action (Brake Pressure is equal Zero) then the load from
Cockpit is used as drive load */
    y[0] = a[2];
}
```

Fig. 6.55 C code function

Table 6.42 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	Vehicle Velocity	km/h	Optional	0
a[1]	Vehicle Acceleration	m/s^2	Optional	0
a[2]	Load Signal	–	Optional	0
a[3]	Brake Pressure	bar	Optional	0
a[4]	Maximum Brake Pressure	bar	Optional	0
a[5]	Brems factor	–	Optional	0
a[6]	a[6]	–	Optional	0
y[0]	Mod Load Signal	–	Optional	0

One output file is produced for each component in the Vehicle Model and each Calculation Task. Data for diagrams are extracted from these files and are shown as Energy Flow Graphics, presentation diagrams for belonging task and standard diagrams for used components.

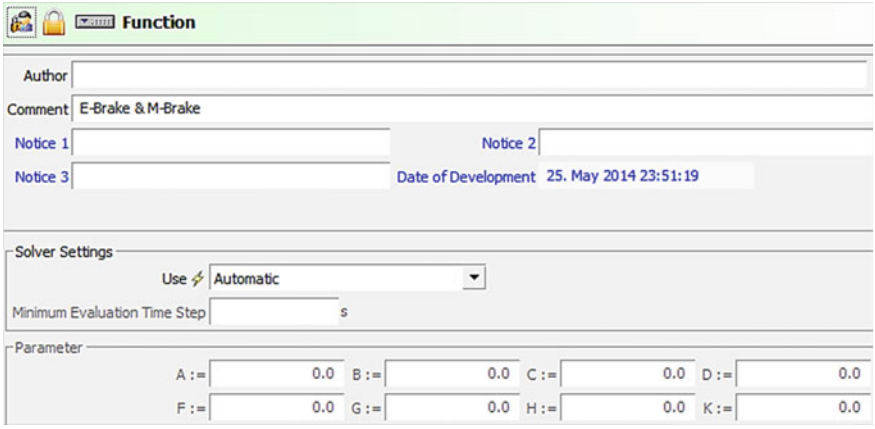


Fig. 6.56 E-Brake & M-Brake input data specifications window

In the tree structure of the Result Manager, all defined Calculation Task folders are shown separately for each task. Those folders with results are shown in color; tasks which are not run are grey. Files of the each Calculation Task are located inside the respective folder. In Result Manager, all components are listed where results have been written in pages mode or data sources mode (Fig. 6.65).

The result output for components is selected with output in the properties window of the respective component. Select as defined in module for output of results in the folder of the corresponding calculation task. There are two types of result outputs available with the Result Manager: standard diagrams and presentation diagrams.

6.2.2 Standard Diagrams

Standard diagrams (Fig. 6.66) are created separately for each component and only contain results of the individual component and represent time histories of the single components.

They have a predefined representation page, which can only be changed in some parts. Standard diagrams are opened by selecting the respective Calculation Task in the tree structure of Result Manager and then selecting the corresponding component.

The pages mode sidebar is divided into a list of predefined standard diagram pages for the respective component and TeimView Assistant with a tree structure of components with all available curves and the current parameter for current diagram of respective component with the list of all used curves. TeimView has two modes tabs: pages and data sources. Pages are used to view results as curves in standard

```
/*Conversion routine*/
/*Converting brake Torque into Pressure for all Brakes (Front & Rear)*/
double E-Brake;
/* Check whether Torque of E-Drive is negative that means the load signal to the
E-Motor is negative.
In this case the corresponding brake Pressure will be calculated*/
if (a[0] < 0 )
{
/* The corresponding Brake  pressure will be determined by using the following
equation:
M = 2 * P * A * eff * u * r * c
with
M: Brake Torque;
P: Brake Pressure;
A: Brake Piston Surface;
eff:  Efficiency;
u: Friction Coefficient;
r: effective Friction Radius;
c: Specific Brake factor.
P=M /(2 *A* eff * u * r* c)
It's simplify the formula for Rear Brake and Front Brake by using
Brake_Factor_Front and Brake_Factor_Rear in order to use the mean value of
both:
Brake_Factor_Front= AF*effF*uF*rF*cF
Brake_Factor_Rear=  AR*effR*uR*rR*cR
It's also to take into account the following ratios: Ratio of Final Drive (iFD) and
Ratio of Transmission (iTR) between the E-Drive and E-Brake.
[P.S. The ratio iTR is equal 1 because there isn't any Gearbox in the model.]
P= M * iFD * iTR/[2 * (Brake_Factor_Front + Brake_Factor_Rear)/2]
The used channel data are then :
a[0] : eDrive_Torque;
a[1] : iFD;
a[2] : iTR;
a[3] : Brake_Factor_Front;
a[4] : Brake_Factor_Rear.
*/
   eBrake = a[0]*2*a[1]*a[2]/(2*(a[3]+a[4]));
}
else
{
/* and if the Torque is positive that means E-Motor drives the vehicle the E-Brake
should be equal Zero */
    E-Brake = 0.;
}
/*Calculation of reduced mechanical E-Brake Function to determine a maximum
value By applying negative load the E-Drive applies a resistance which generates
electrical power. In this case the mechanical power required for breaking will be
reduced by the power which the E-Motor has recuperated.
That means the vehicle will at first be electrically braked and The rest required
brake energie will be provided by mechanical brakes */
if ((E-Brake+a[5])>0.0)
{
    y[0]= (E-Brake+a[5]);
}
else
{
    y[0]= 0.0;
}
```

Fig. 6.57 C code function

Table 6.43 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	eDrive_Torque	Nm	Optional	0
a[1]	iFD (Ratio of Final Drive)	–	Optional	0
a[2]	iTR (Ratio of Final Transmission)	–	Optional	0
a[3]	Brake_Factor_Front	–	Optional	0
a[4]	Brake_Factor_Rear	–	Optional	0
a[5]	Brake Pressure_Driver	Pa	Optional	0
y[0]	BRK_dp_Recup	Pa	Optional	0

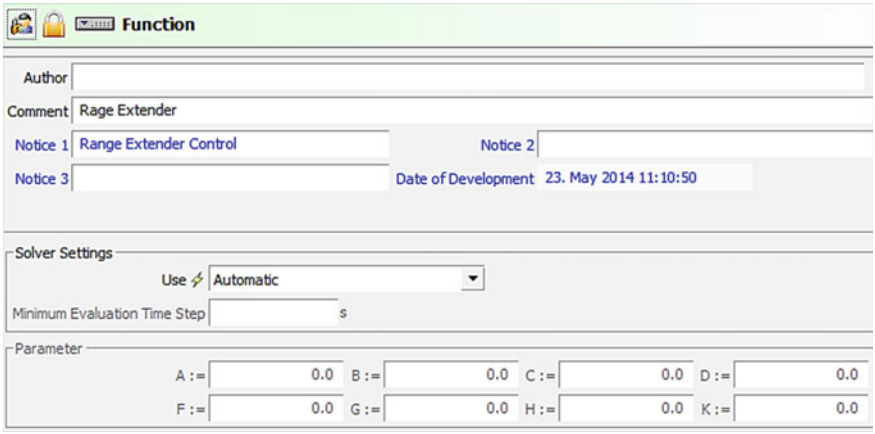


Fig. 6.58 Range extender control input data specifications window

diagram and data sources in tables as numerical data for the respective component for analyzing and extracting.

The data sources mode sidebar (Fig. 6.67) has a tree structure where the data source, data file, and table are shown. In data source view is a list of all curve data that can be shown.

Energy Flow Graphics feature can be selected in the Result Manager (Fig. 6.68). An animation shows the flow between the drivetrain components over time of the following parameters: Current [A], Energy Stored [kJ], Energy [kJ], Power [kW], Speed [1/min], Velocity [km/h], Torque [Nm], Force [N], Voltage [V].

The animation can be controlled by appropriate switches (play, pause, step-wise, stop, repeat, velocity). A time-bar, showing the actual simulation time, can be moved to a certain time-step with the mouse.

Below the flow graphics a monitor is shown which displays the result curves of selected components. With a zoom-option, the horizontal direction can be scaled so that long cycles can also be viewed properly.

```
/* Starting && Shut down Engine and Charging Battery*/
int  operatingMode;
if(realTime<=0.0) { operatingMode = 0; }
/*Checking whether the State of Charge exceeds the Minimum Value*/
if (a[0] <  a[1] )
{
/* Range extending: In this case the Engine should be started and Generator have
to generate energy into Battery. */
  operatingMode=1;
}
if  (a[0] >  a[2] )
{
/* Pure electrical Drive: In this case the Engine is turned off and the E-Motor per-
form the eDriving. */
  operatingMode=0;
}
if (operatingMode)
{
/* Start Switch for Engine have to be set. The load signal for Generator should be
applied when the engine is around its optimum operating area.
The load signal to the Engine is provided by PID which controls the Engine speed
to the pre-defined speed level. */
   y[0] = 1; /*start switch Gen*/
   y[1] = 0; /*load signal Gen init*/
   if (a[4]> (a[6]-50)) /*check on the ICE speed*/
   {
      y[1] = -0.5; /*load signal Gen*/
    }
      y[2] = a[3]; /*start switch ICE*/
   y[3] = a[5]; /*load signal ICE*/
    if ( (a[4]< (a[6]-50)) && (a[5]>0.5) ) /*check on the ICE speed and limit the
value*/
   {
      y[3] = 0.5; /*load signal ICE*/
    }
}
if (!operatingMode)
{
/* When ICE is turned off, all of the set values to the Range Extender components
are set to not-active. */
   y[0] = 0.0;
   y[1] = 0.0;
   y[2] = 0.0;
   y[3] = 0.0;
}
```

Fig. 6.59 C code function

Table 6.44 Description of Data Bus

Data Bus Channel	Description	Unit	Connection	Decouple
a[0]	SOC_Act	%	Optional	0
a[1]	SOC_Min	%	Optional	0
a[2]	SOC_Max	%	Optional	0
a[3]	Start_Switch _CP	–	Optional	0
a[4]	Engine Speed	1/min	Optional	0
a[5]	Load_Signal_Engine	–	Optional	0
a[6]	Desired Engine Speed	1/min	Optional	0
y[0]	Start_Switch_Gen	–	Optional	0
y[1]	Load_Signal_Gen	–	Optional	0
y[2]	Start Switch_Engine	–	Optional	0
y[3]	Load_Signal_Engine	–	Optional	0

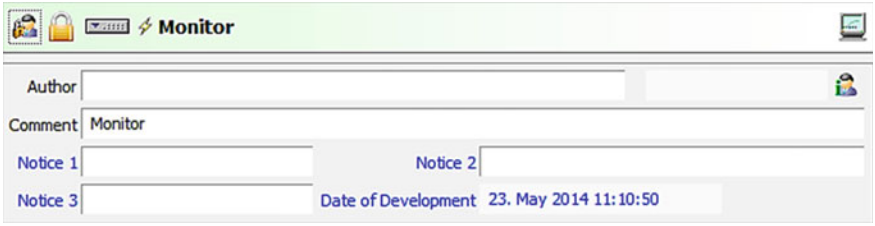


Fig. 6.60 Monitor input data specifications window

Table 6.45 Description of Data Bus

Data Bus Channel	Description	Unit
Input 0	LoadSignal_Cockpit	–
Input 1	Velocity	km/h
Input 2	Torque_eDrive	Nm
Input 3	SOC (State of Charge)	%
Input 4	Engine_Speed	rpm

In addition to the graphical representation, the associated values can also be displayed in the monitor as well as in the drivetrain flow graphics.

The values of the Energy Flow Graphics can also be displayed in a pie chart.

Clicking the button EFG pie chart opens an area where the segments can be added or removed with the buttons "+" and "−."

The association between a segment and a component parameter can be done by marking the segment in the segment list and then doing a left mouse-click on a so-called connector of the component (Fig. 6.69). Several connectors can be chosen for one segment. In that case, the segment represents the sum of all associated values. The segment list consists of the absolute segment values as well as of the values in terms of percentages.

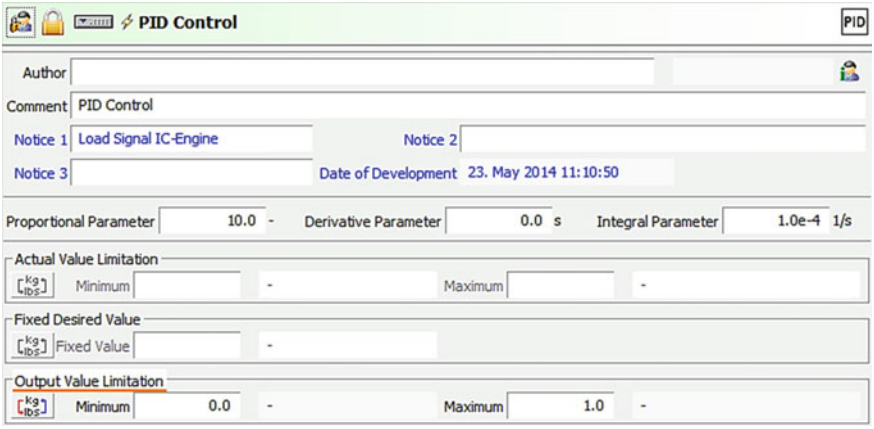


Fig. 6.61 PID control input data specifications window

Table 6.46 PID control input data

Name	Value	Unit
Proportional Parameter	10.00	–
Derivative Parameter	0.000	s
Integral Parameter	1.0e−4	1/s
Output Value Minimum	0.000	–
Output Value Maximum	1.000	–

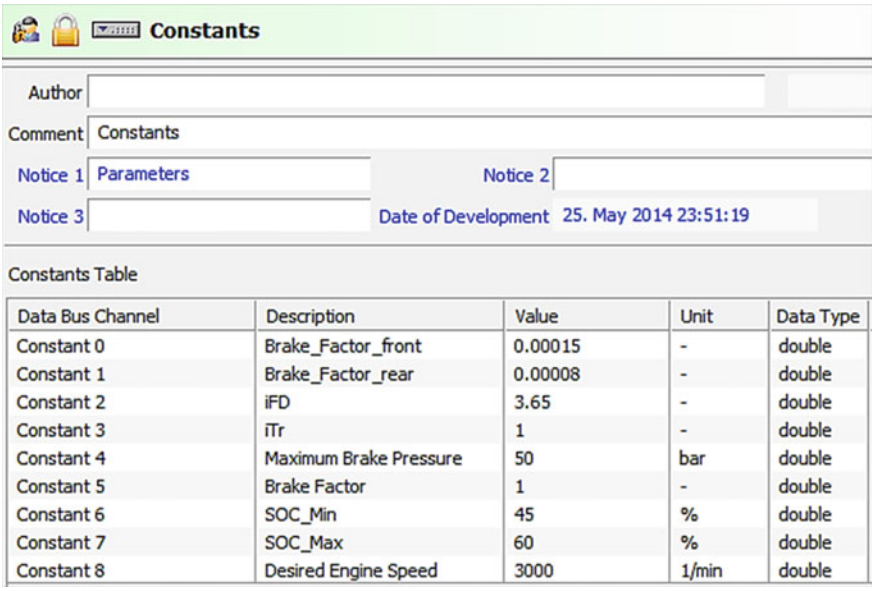


Fig. 6.62 Constants input data specifications window

Table 6.47 Constants table data

Data Bus Channel	Description	Value	Unit	Type
Constant 0	Brake_Factor_Front	0.00015	–	Double
Constant 1	Brake_Factor_Rear	0.00008	–	Double
Constant 2	iFD (Ratio of Final Drive)	3.650	–	Double
Constant 3	iTR (Ratio of Final Transmission)	1.000	–	Double
Constant 4	Maximum Brake Pressure	50.00	bar	Double
Constant 5	Brake Factor	1.000	–	Double
Constant 6	SOC_Min	45.00	%	Double
Constant 7	SOC_Max	60.00	%	Double
Constant 8	Desired Engine Speed	3000	1/min	Double

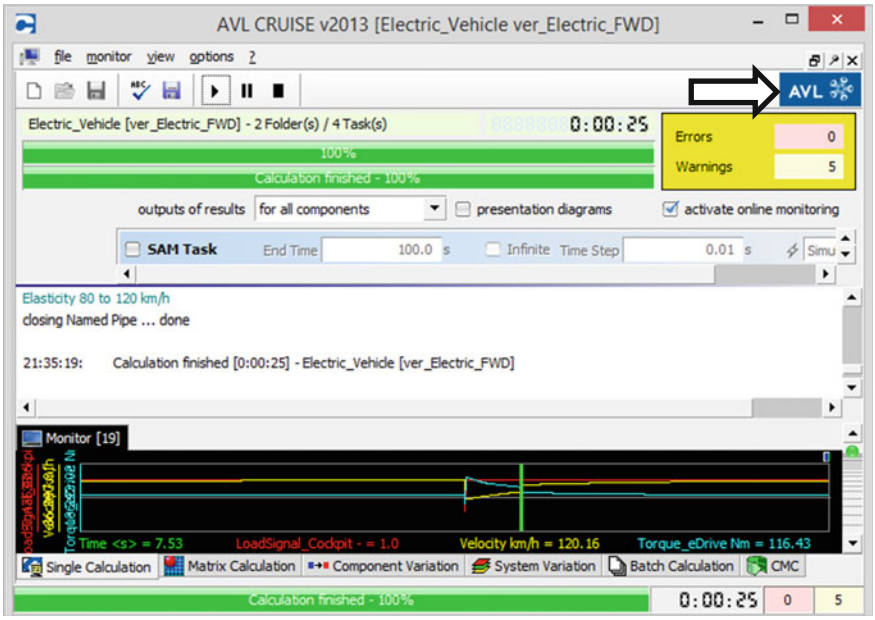


Fig. 6.63 Start calculation

To evaluate the economy characteristics the simulation was running a typical NEDC cycle (Fig. 6.70). The total distance of this cycle is 10.931 m, the total time is 1180 s, idle standing time is 267 s, average speed including stops is 33.35 km/h, average driving speed excluding stops is 43.10 km/h, average acceleration is 0.506 m/s^2 and maximum acceleration is 1.042 m/s^2.

After running the simulation, all the results can be exported into graphs: the slip signal for all the wheels (Fig. 6.71), the required friction coefficient (Fig. 6.72), comparison of front and back friction coefficient (Fig. 6.73), electrical power,

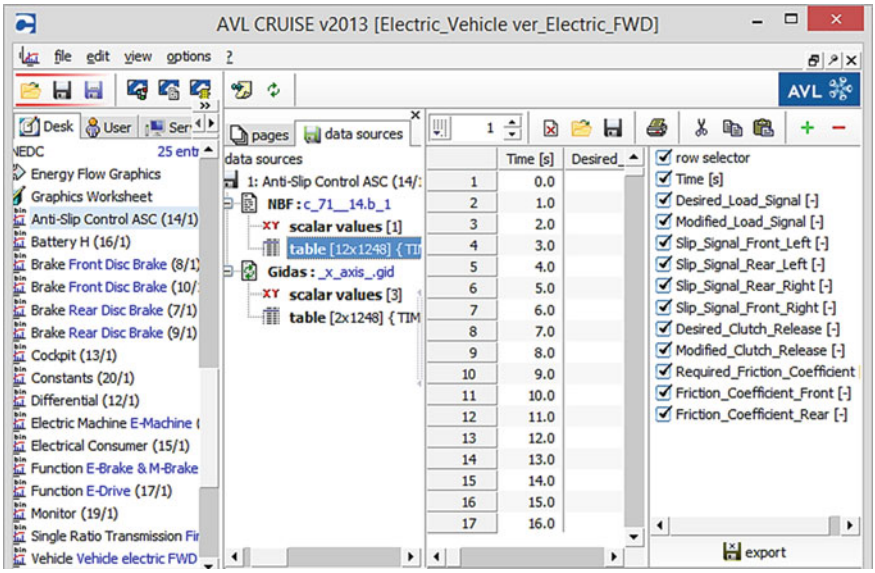


Fig. 6.64 Result Manager window

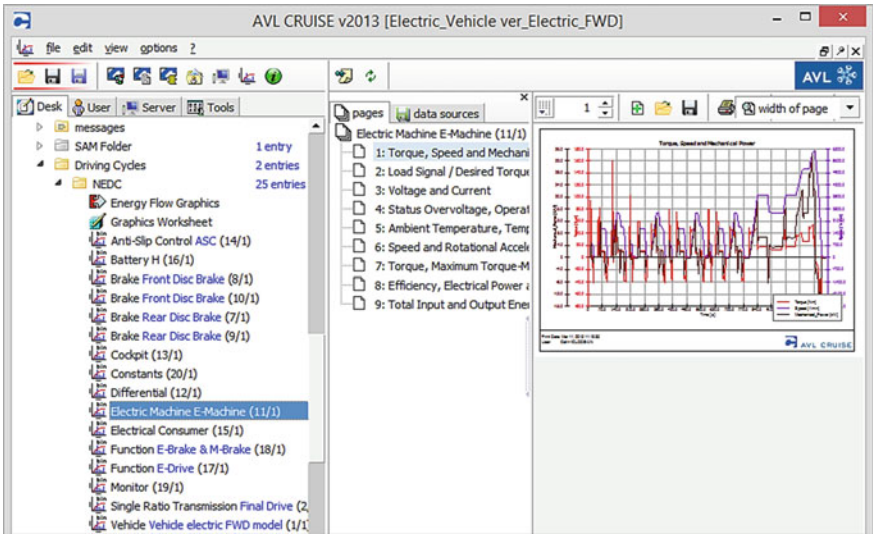


Fig. 6.65 Result Manager pages mode

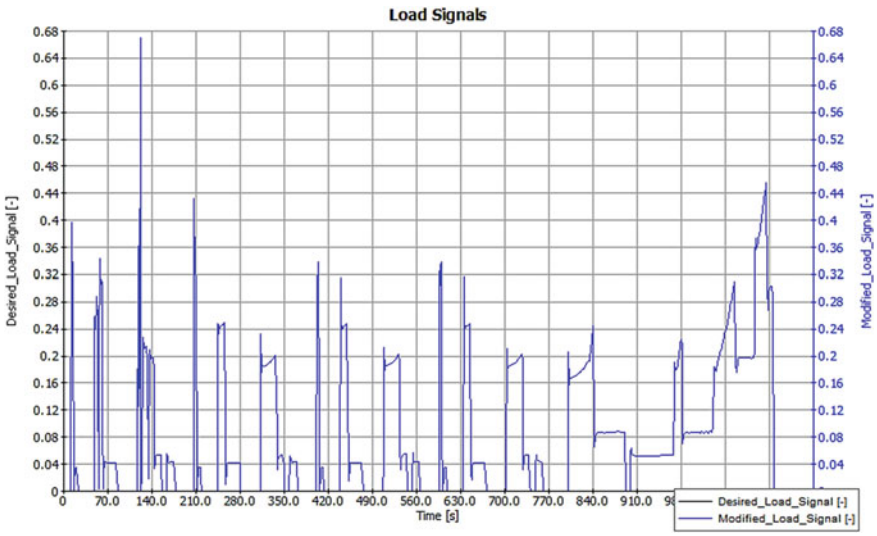


Fig. 6.66 Standard diagrams

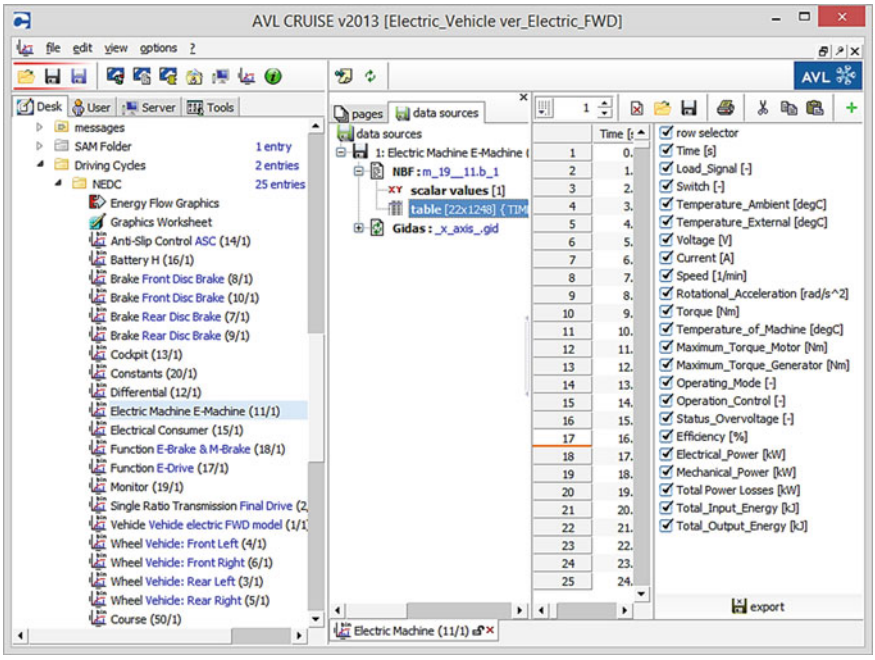


Fig. 6.67 Result Manager data sources mode

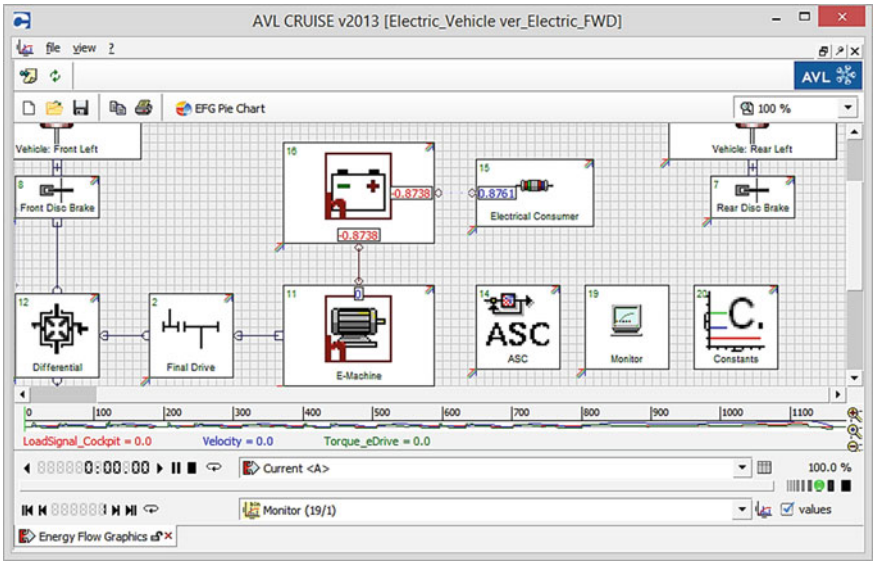


Fig. 6.68 Energy Flow Graphics



Fig. 6.69 Energy Flow Graphics pie chart

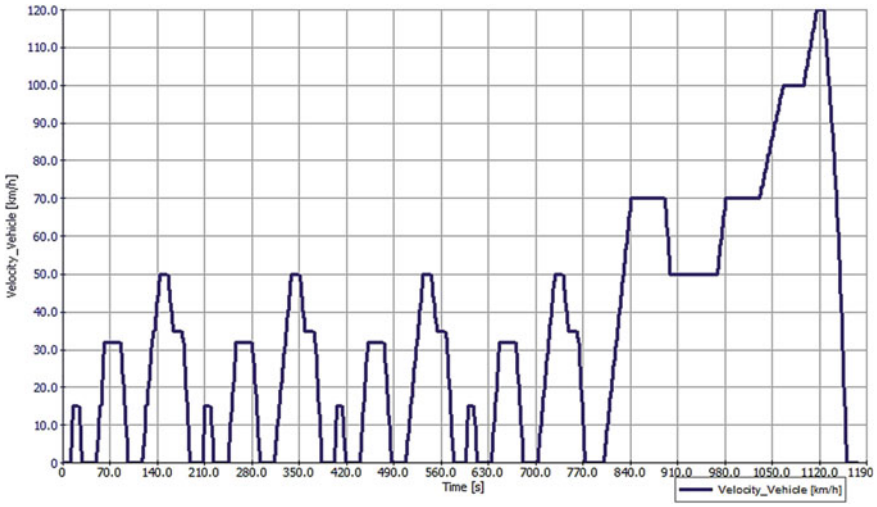


Fig. 6.70 NEDC typical cycle

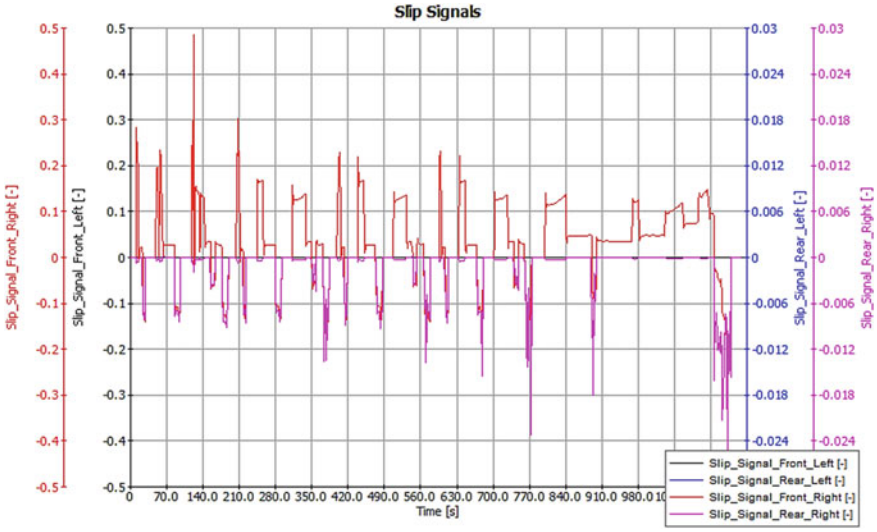


Fig. 6.71 The slip signal for all the wheels

maximum power out, and power input (Fig. 6.74), voltage, current, charge, and State of Charge (Fig. 6.75), and electrical power and power loss (Fig. 6.76), total input and output energy and charge (Fig. 6.77), speed, braking torque, and brake

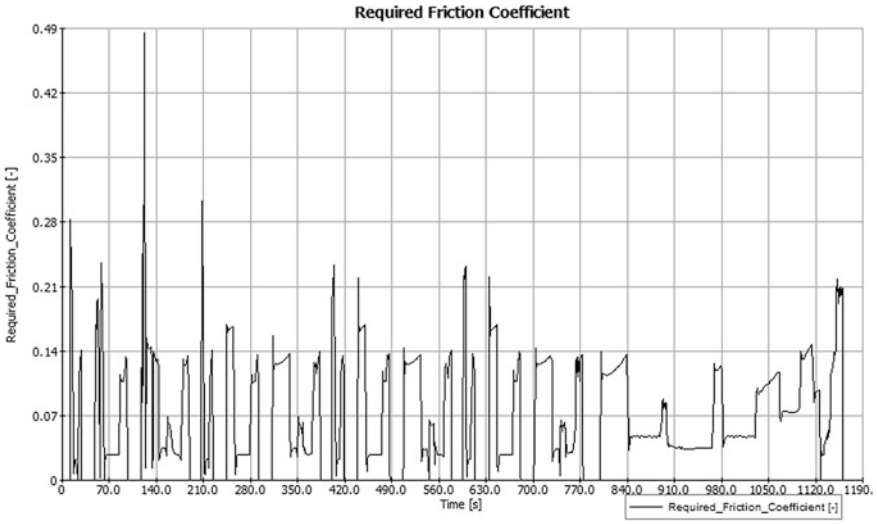


Fig. 6.72 The required friction coefficient

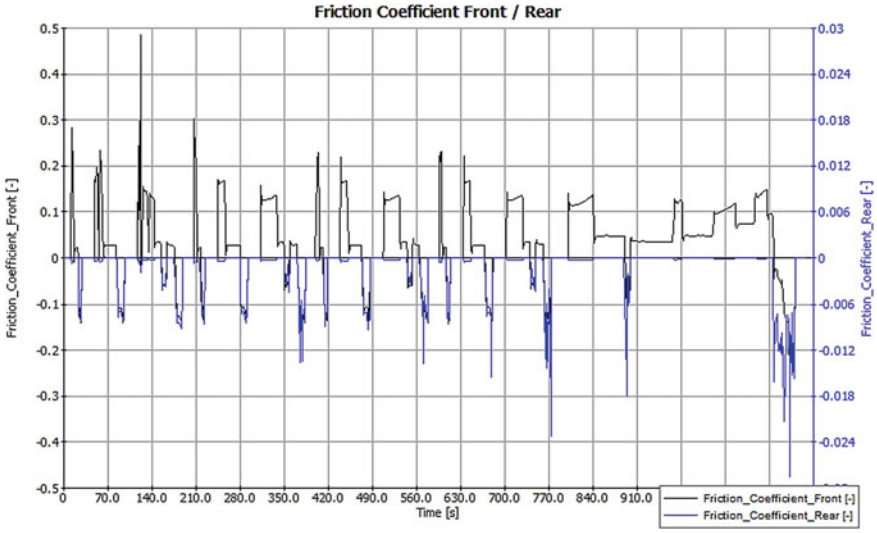


Fig. 6.73 Comparison of front and back friction coefficient

power (Fig. 6.78), brake pressure, braking torque and brake power (Fig. 6.79), braking torque and rotational acceleration (Fig. 6.80), acceleration velocity and distance (Fig. 6.81), acceleration pedal travel, brake pedal force and clutch pedal

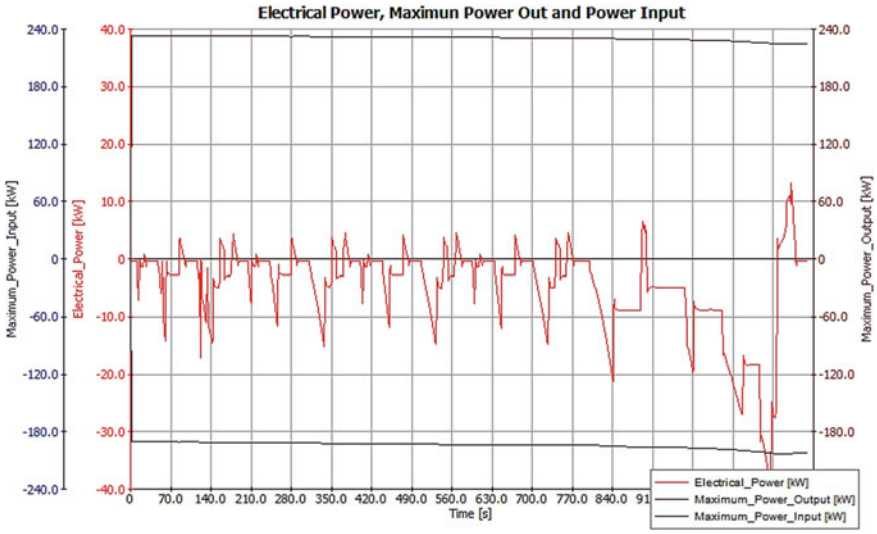


Fig. 6.74 Electrical power, maximum power out and power inputs

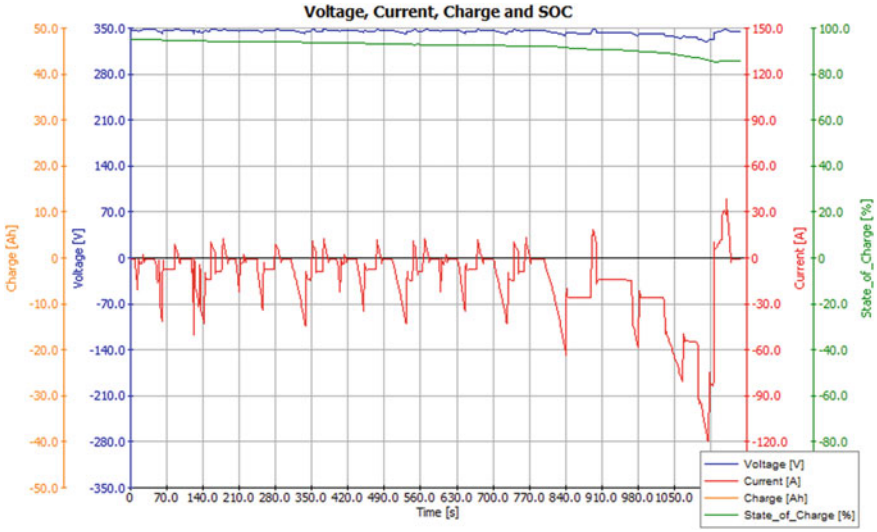


Fig. 6.75 Voltage, current, charge, and State of Charge

travel (Fig. 6.82), load signal, brake pressure, and clutch release (Fig. 6.83), real time, current gear and velocity (Fig. 6.84), rotational accelerations (Fig. 6.85), torques (Fig. 6.86), power loss and efficiency (Fig. 6.87), torque, speed, and

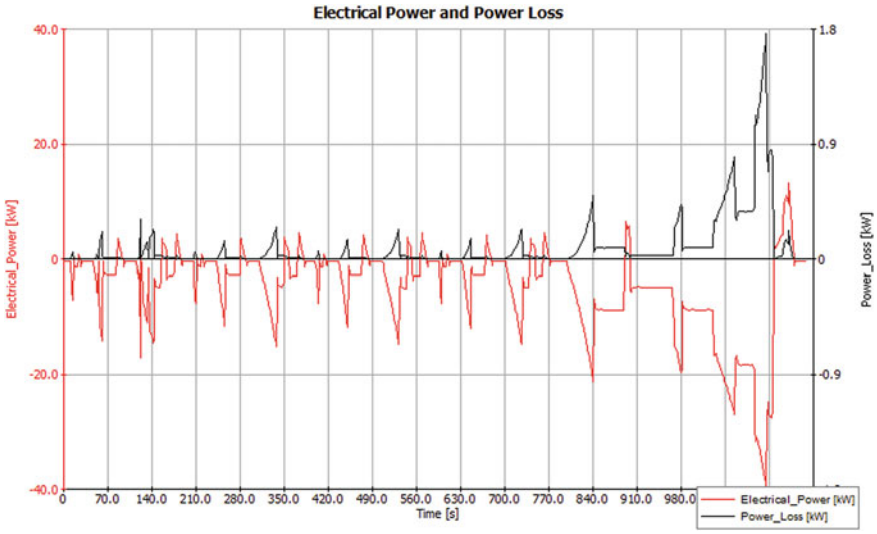


Fig. 6.76 Electrical power and power loss

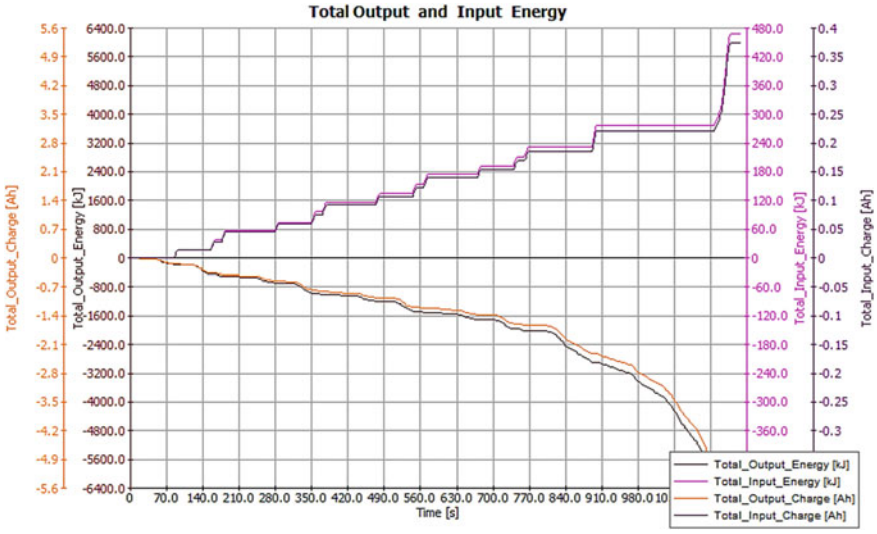


Fig. 6.77 Total input and output energy and charge

mechanical power (Fig. 6.88), torque, maximum torque—motor and maximum torque—generator (Fig. 6.89), efficiency, electrical power, and power loss (Fig. 6.90), total input and output energy (Fig. 6.91).

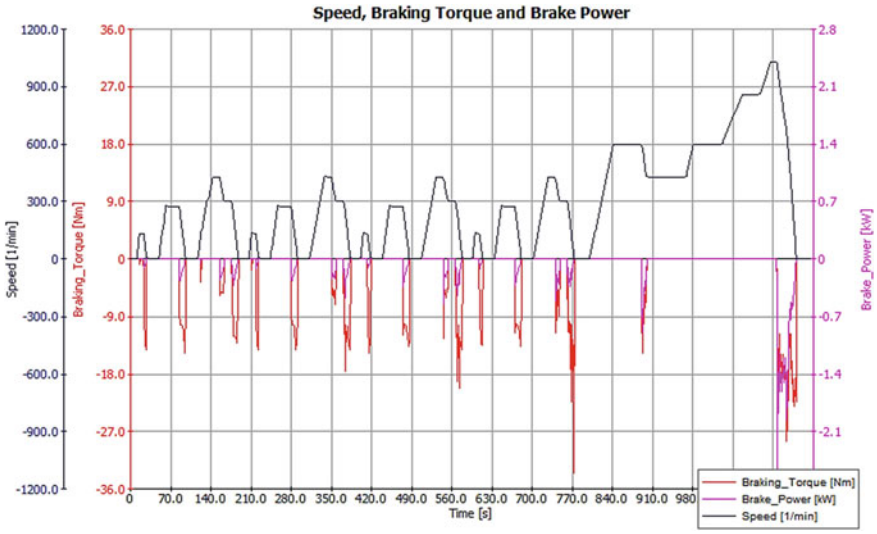


Fig. 6.78 Speed, braking torque and brake power

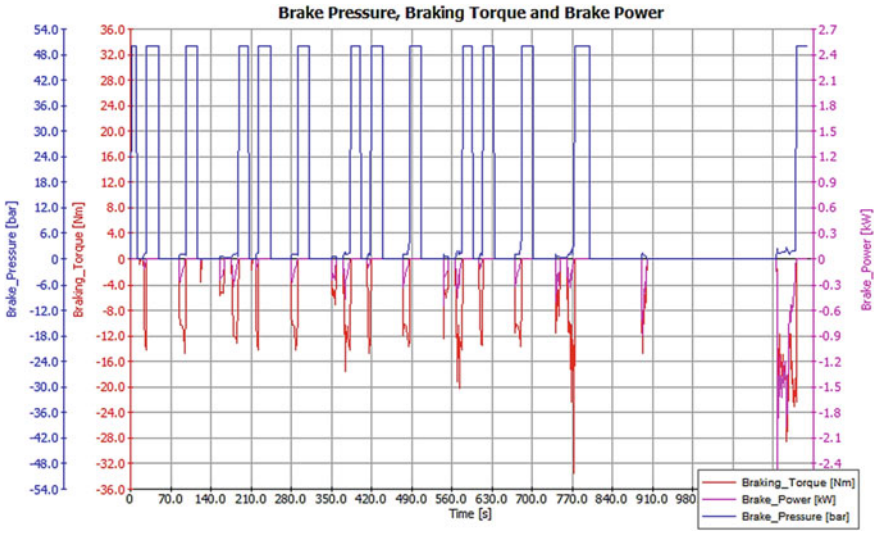


Fig. 6.79 Brake pressure, braking torque, and brake power

For all inputs and outputs, a specific graph can be made: switch and resistance (Fig. 6.92), e-drive torque input (Fig. 6.93), driver brake pressure (Fig. 6.94), input vehicle velocity (Fig. 6.95), input vehicle acceleration (Fig. 6.96), input load signal

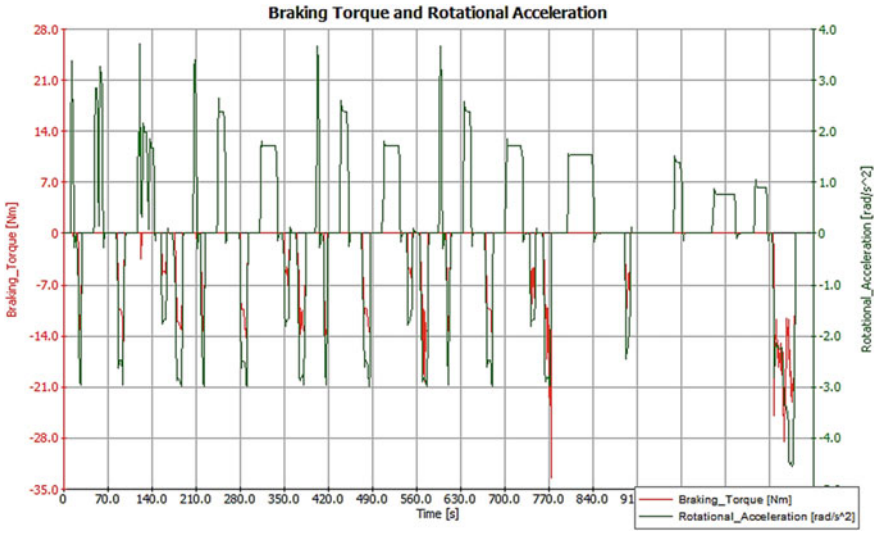


Fig. 6.80 Braking torque and rotational acceleration

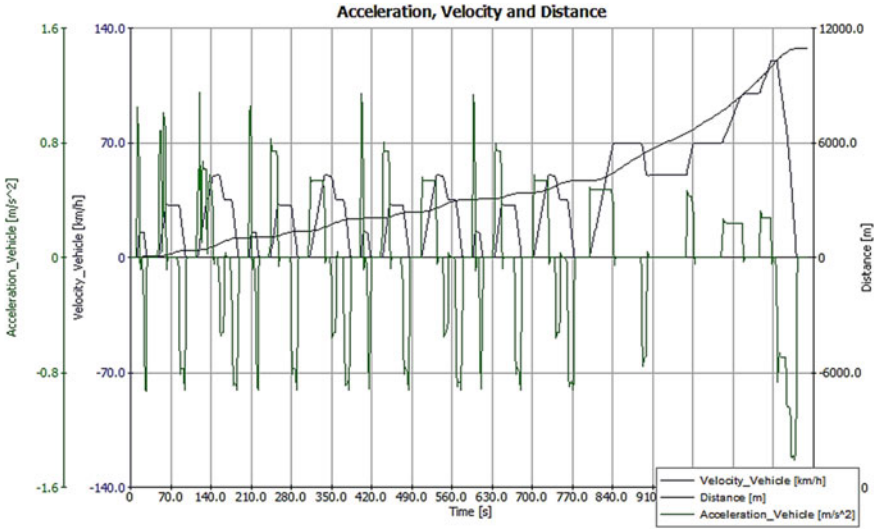


Fig. 6.81 Acceleration velocity and distance

(Fig. 6.97), input brake pressure (Fig. 6.98), mod load signal (Fig. 6.99), input load signal cockpit (Fig. 6.100), speed input and output (Fig. 6.101), rotational acceleration input and output (Fig. 6.102), efficiency and torque loss (Fig. 6.103),

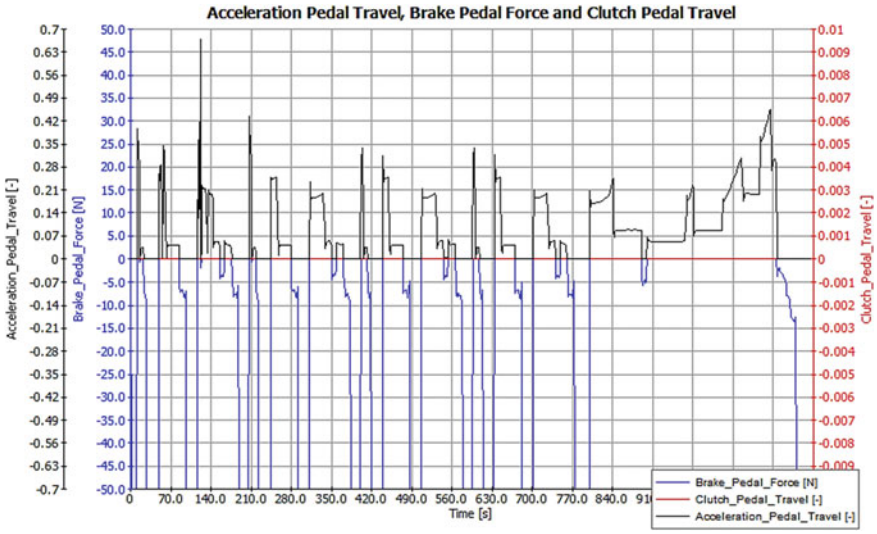


Fig. 6.82 Acceleration pedal travel, brake pedal force, and clutch pedal travel

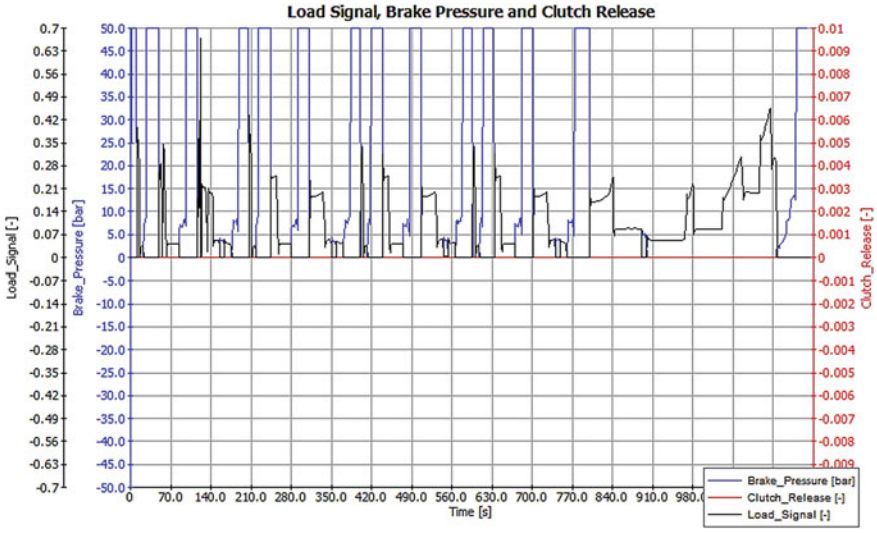


Fig. 6.83 Load signal, brake pressure, and clutch release

air resistance force, resistance force and traction force (Fig. 6.104), wheel loads front (Fig. 6.105), wheel loads rear (Fig. 6.106), axle loads (Fig. 6.107), friction coefficient and friction coefficient exploit (Fig. 6.108), longitudinal force and slip

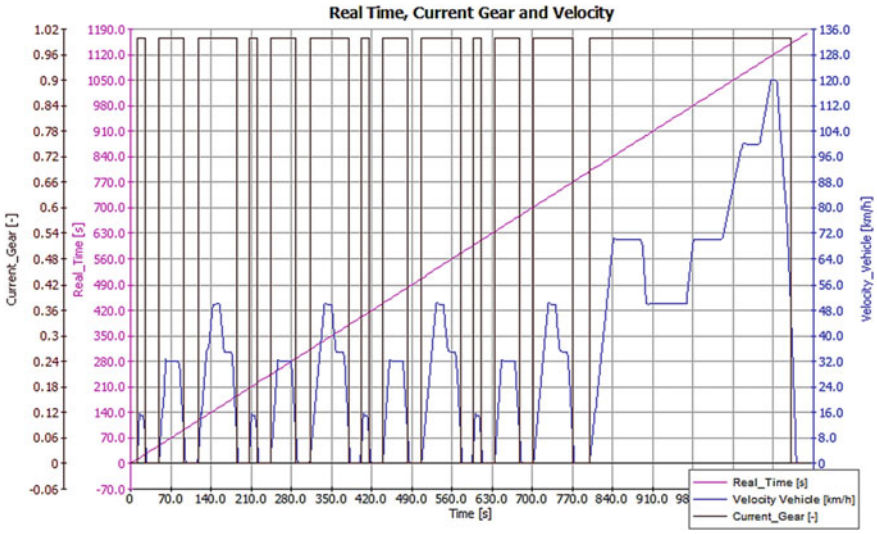


Fig. 6.84 Real time, current gear, and velocity

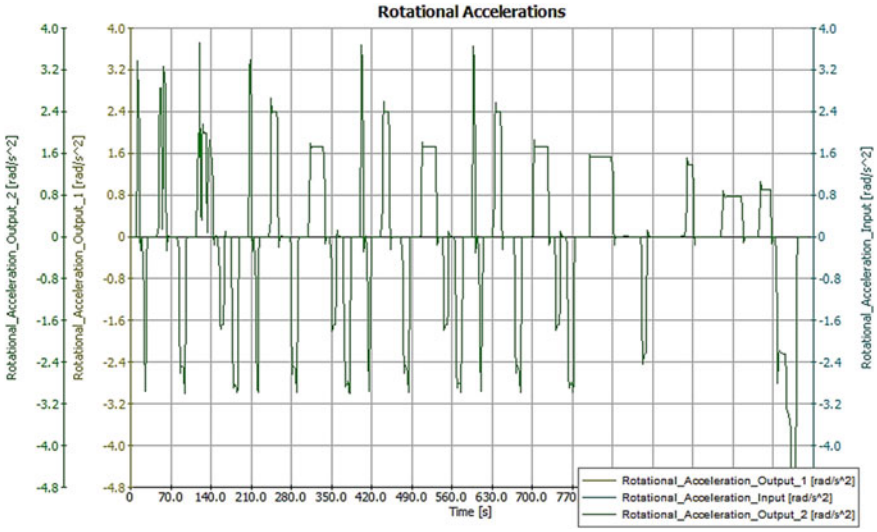


Fig. 6.85 Rotational accelerations

(Fig. 6.109), desired, current, minimum, and maximum velocity (Fig. 6.110), clutch pedal travel and acceleration pedal travel (Fig. 6.111), brake pedal travel and acceleration pedal travel (Fig. 6.112), clutch pedal travel and gear (Fig. 6.113), brake pedal travel, and power of all brakes (Fig. 6.114).

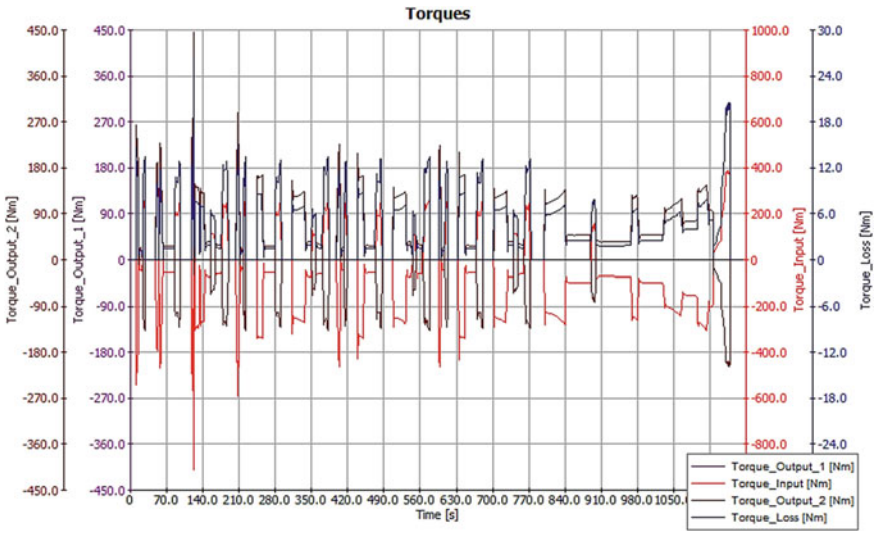


Fig. 6.86 Torques

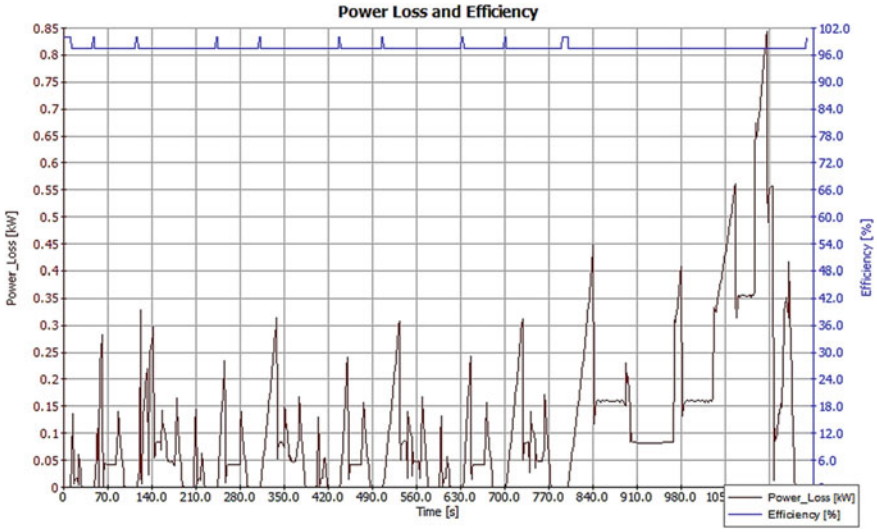


Fig. 6.87 Power loss and efficiency

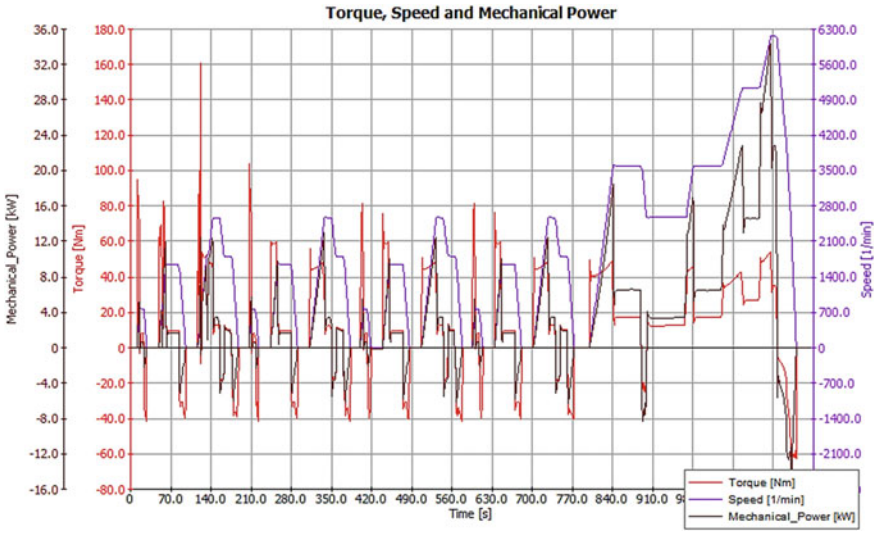


Fig. 6.88 Torque, speed, and mechanical power

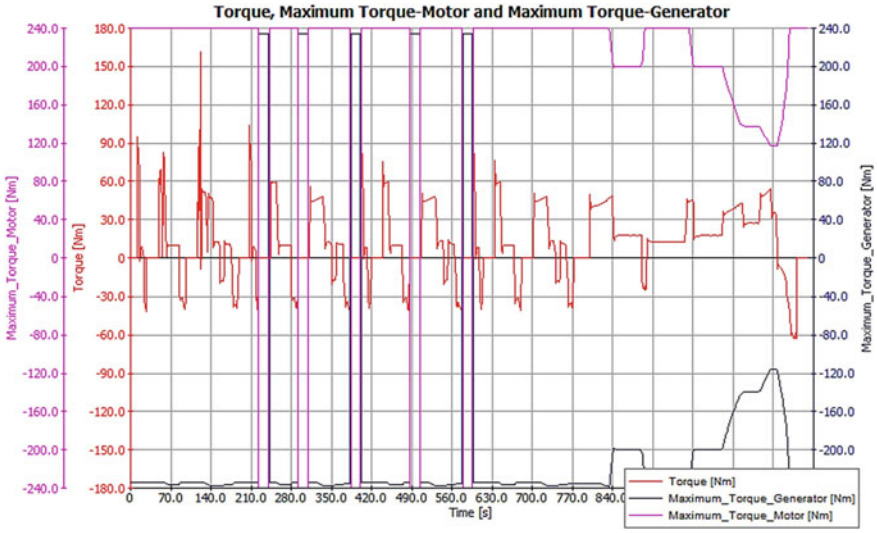


Fig. 6.89 Torque, maximum torque—motor, and maximum torque—generator

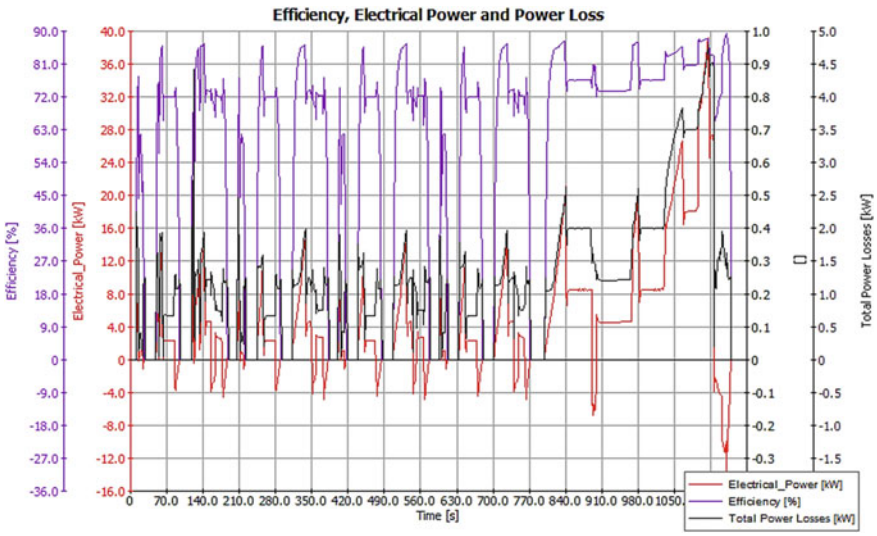


Fig. 6.90 Efficiency, electrical power, and power loss

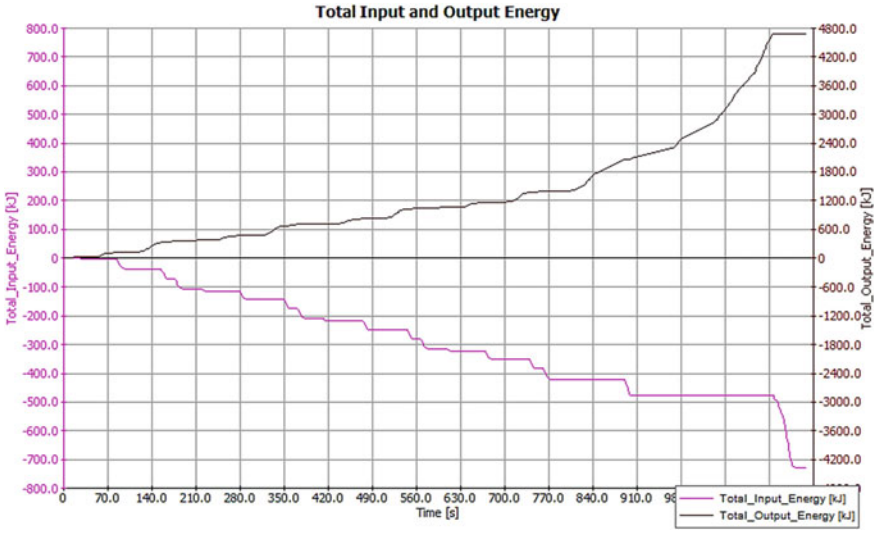


Fig. 6.91 Total input and output energy

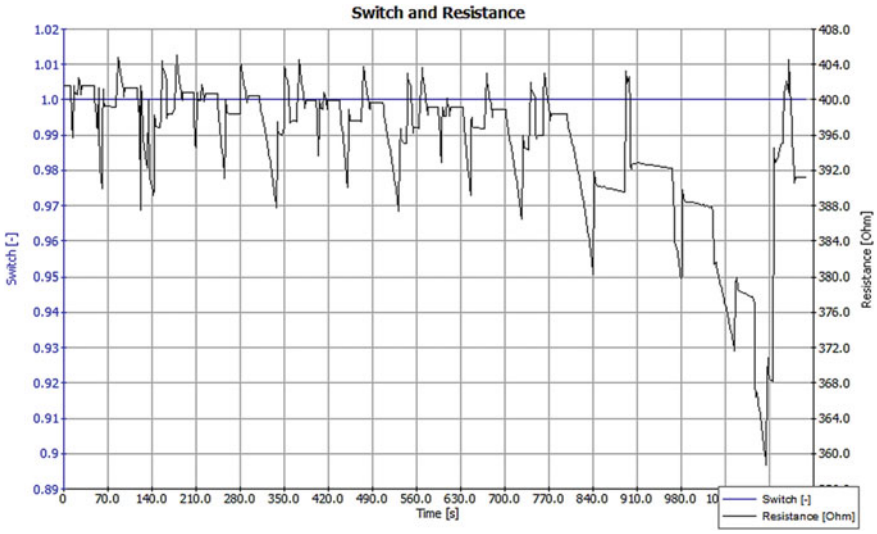


Fig. 6.92 Switch and resistance

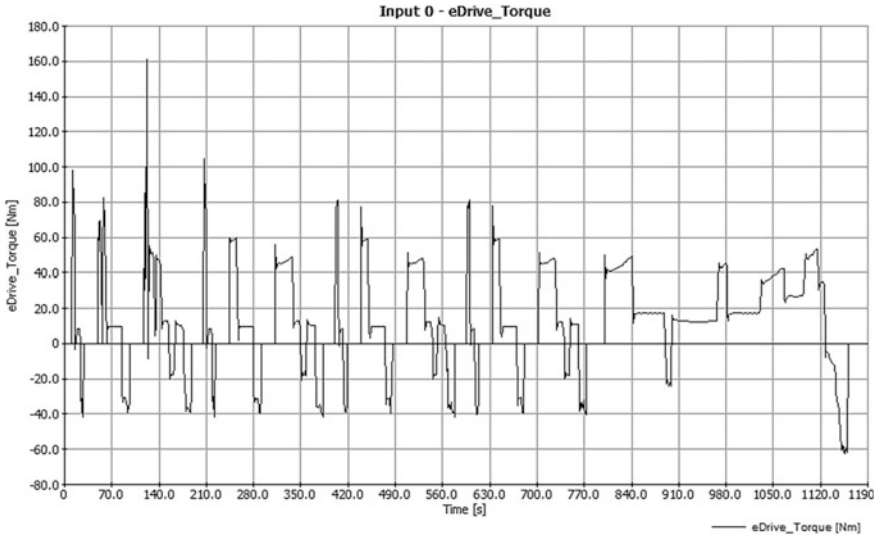


Fig. 6.93 E-drive torque input

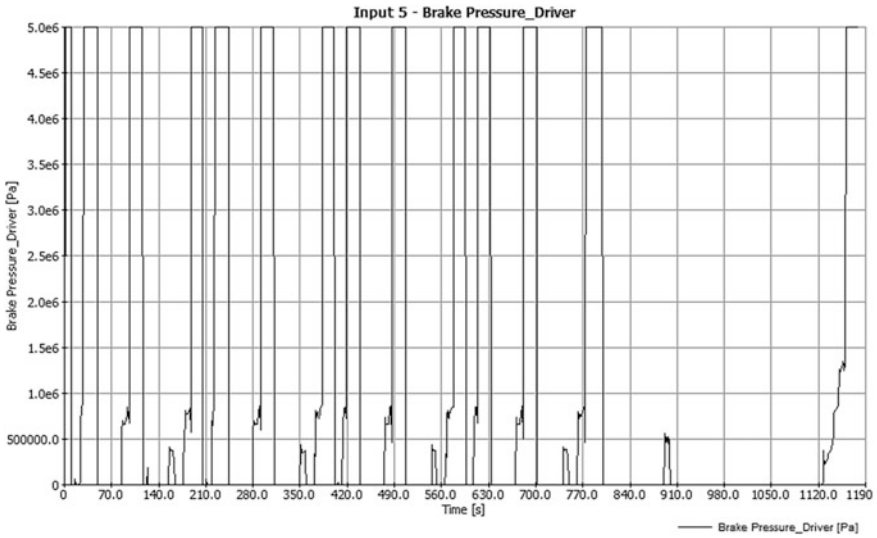


Fig. 6.94 Driver brake pressure

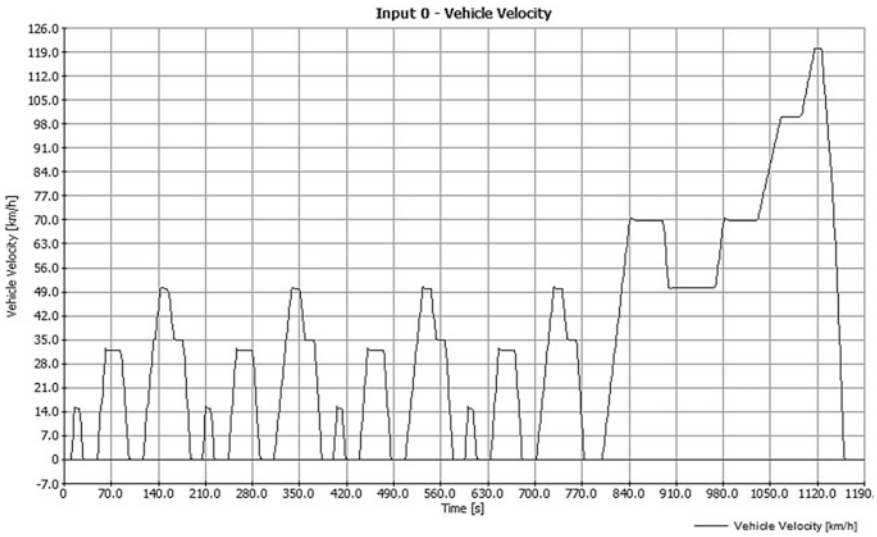


Fig. 6.95 Input vehicle velocity

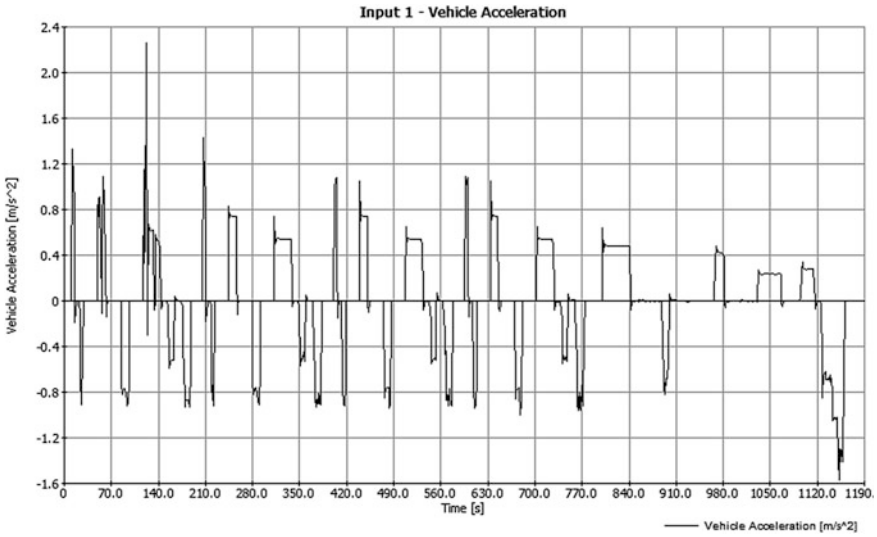


Fig. 6.96 Input vehicle acceleration

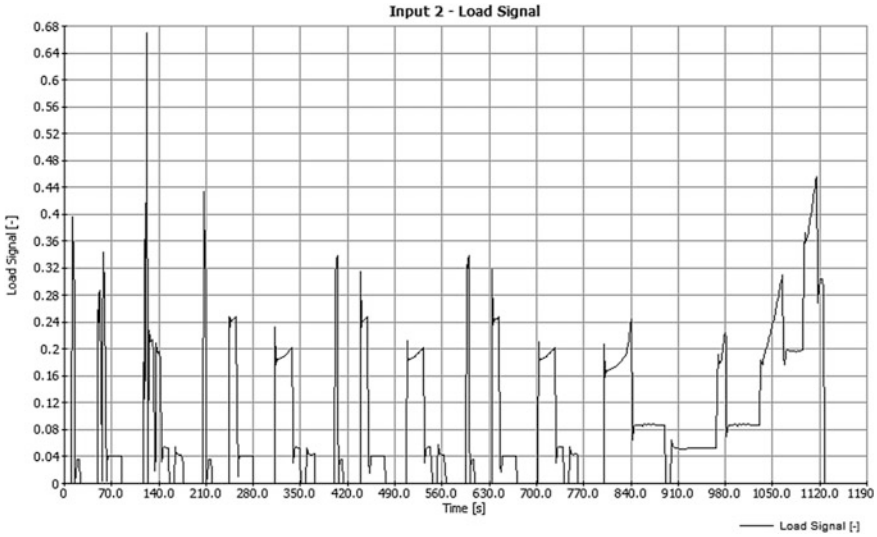


Fig. 6.97 Input load signal

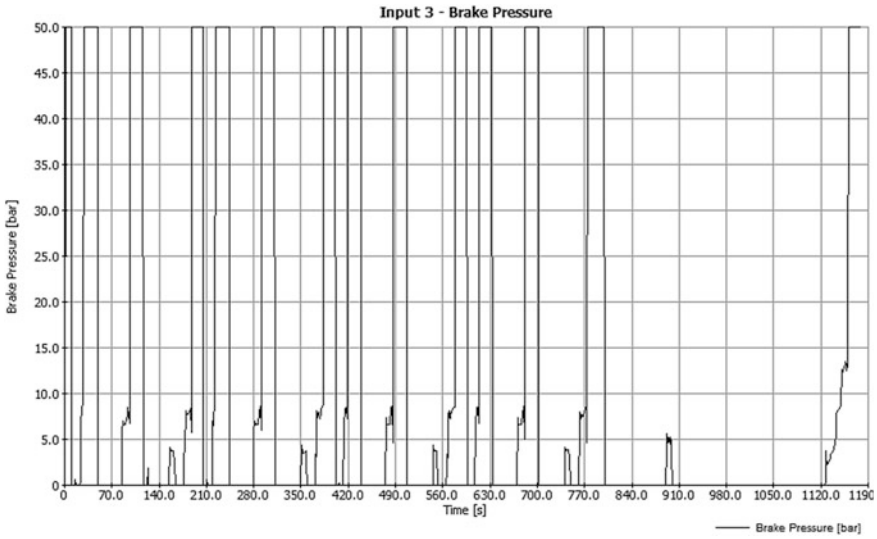


Fig. 6.98 Input brake pressure

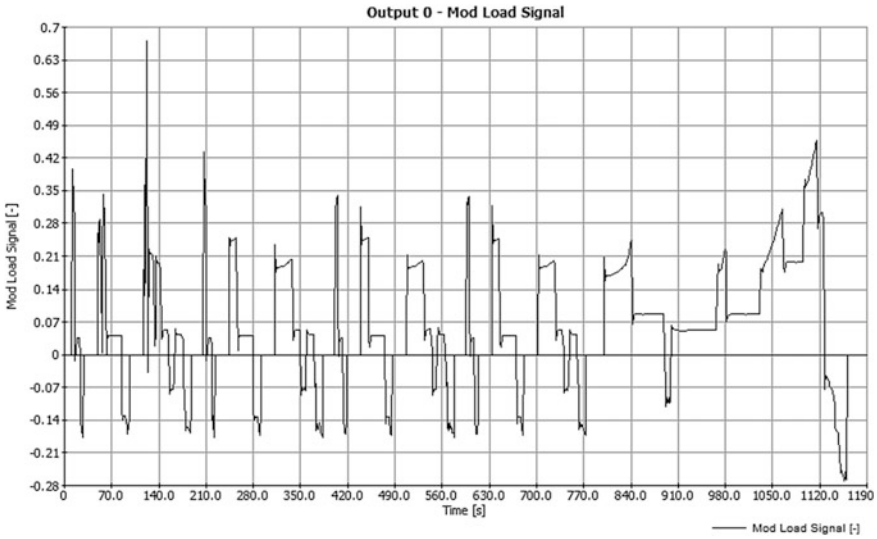


Fig. 6.99 Mode load signal

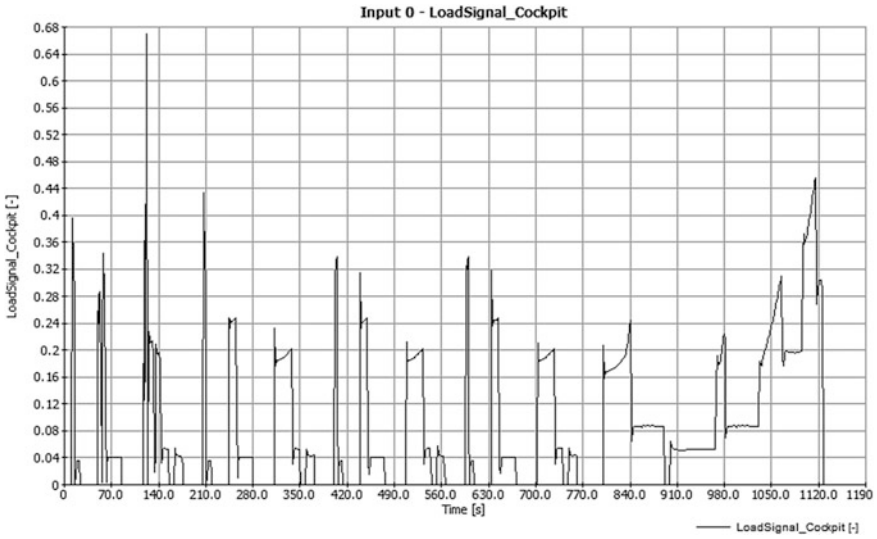


Fig. 6.100 Input load signal cockpit

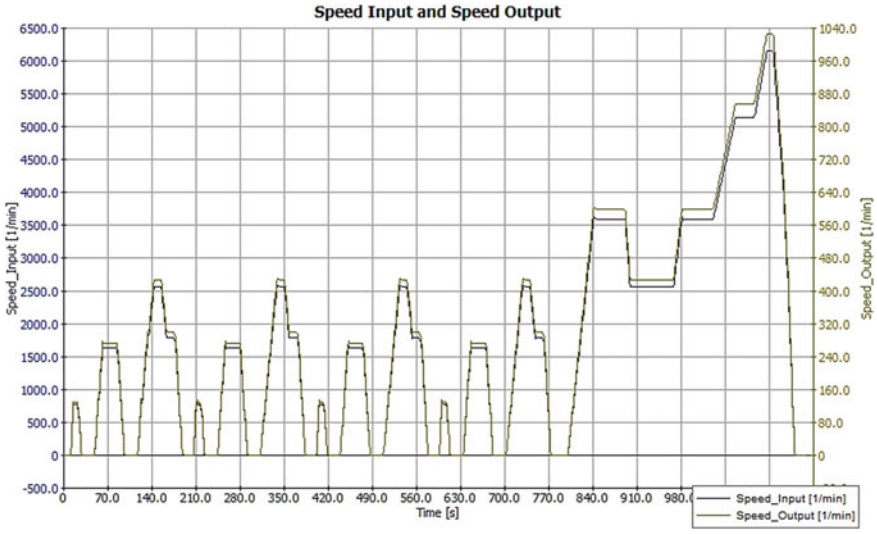


Fig. 6.101 Speed input and output

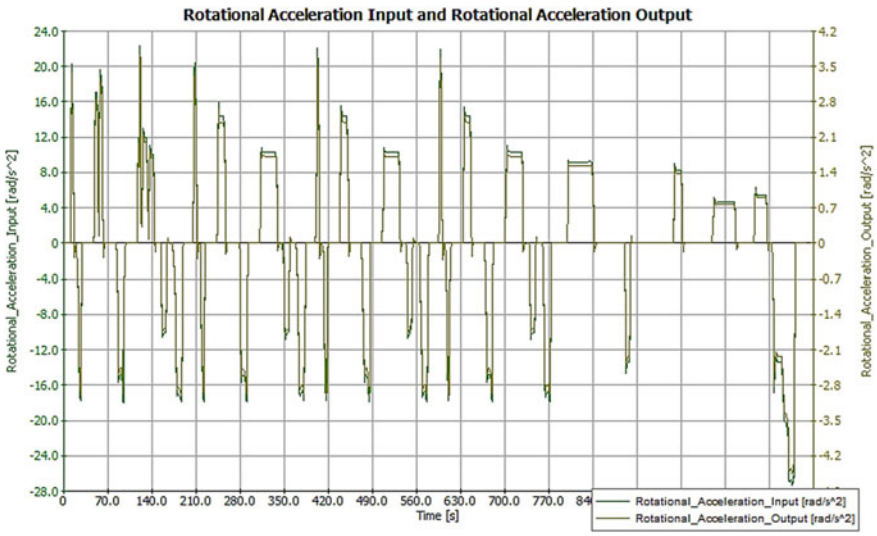


Fig. 6.102 Rotational acceleration input and output

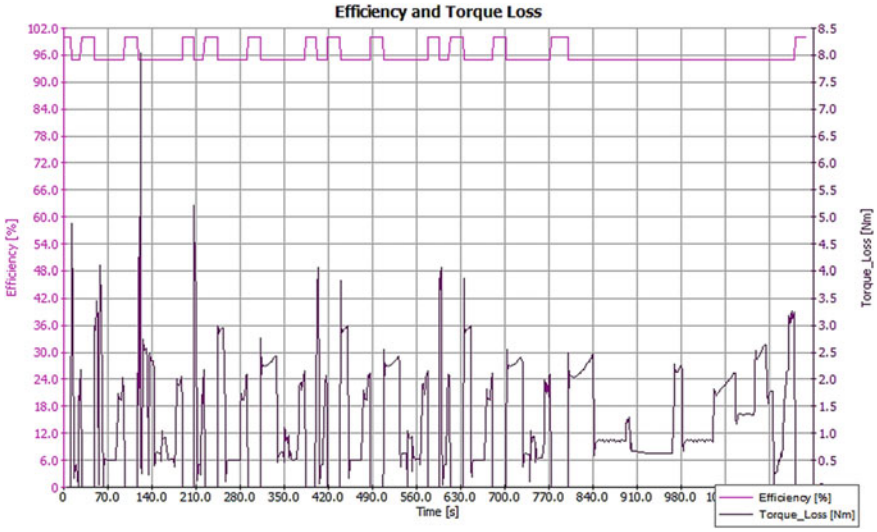


Fig. 6.103 Efficiency and torque loss

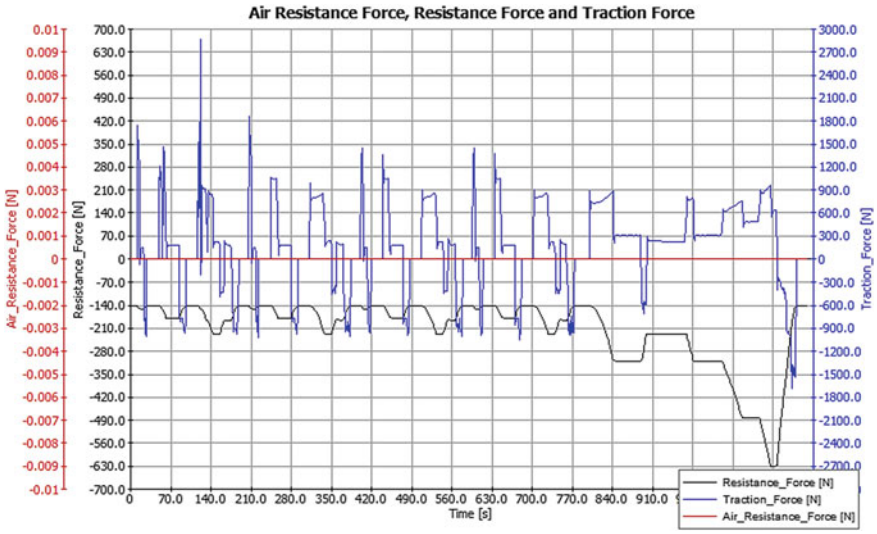


Fig. 6.104 Air resistance force, resistance force and traction force

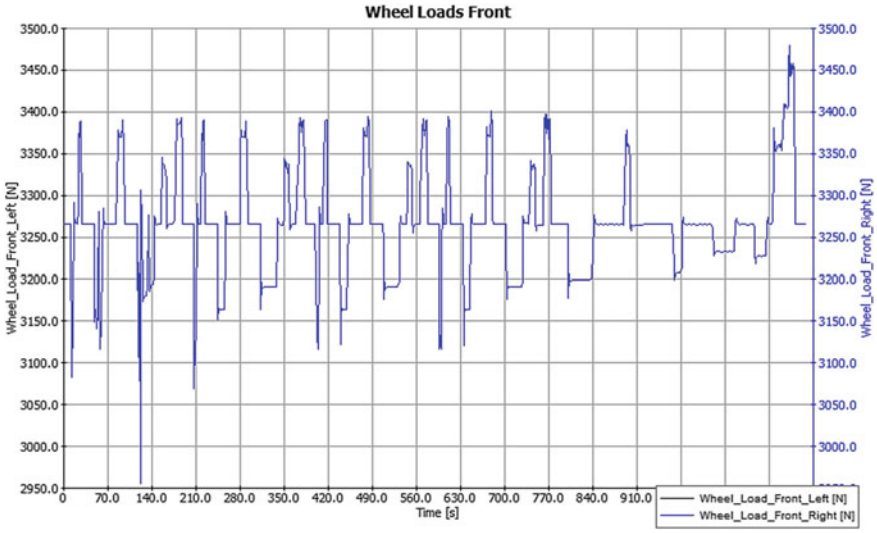


Fig. 6.105 Wheel loads front

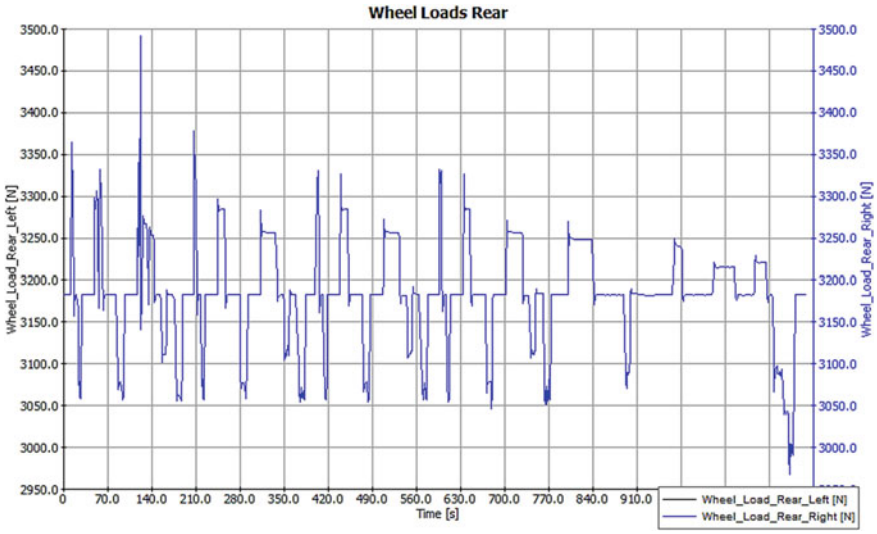


Fig. 6.106 Wheel loads rear

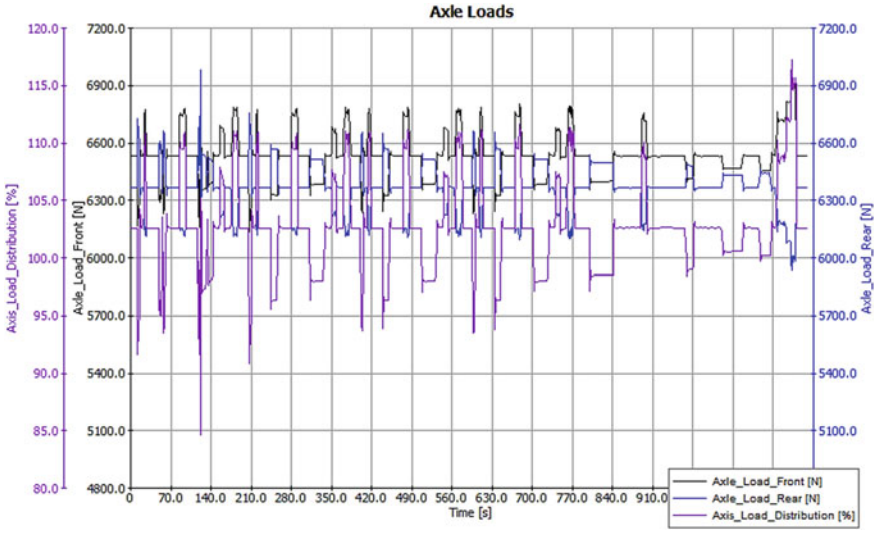


Fig. 6.107 Axle loads

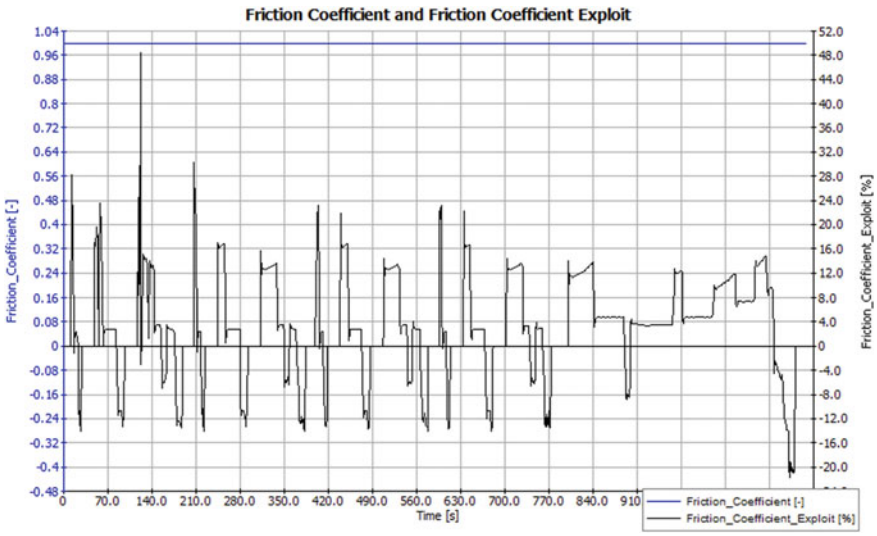


Fig. 6.108 Friction coefficient and friction coefficient exploit

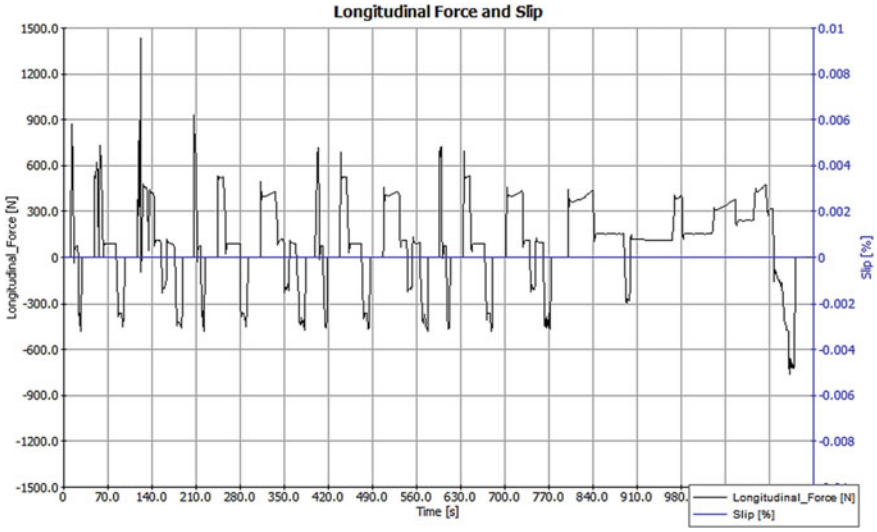


Fig. 6.109 Longitudinal force and slip

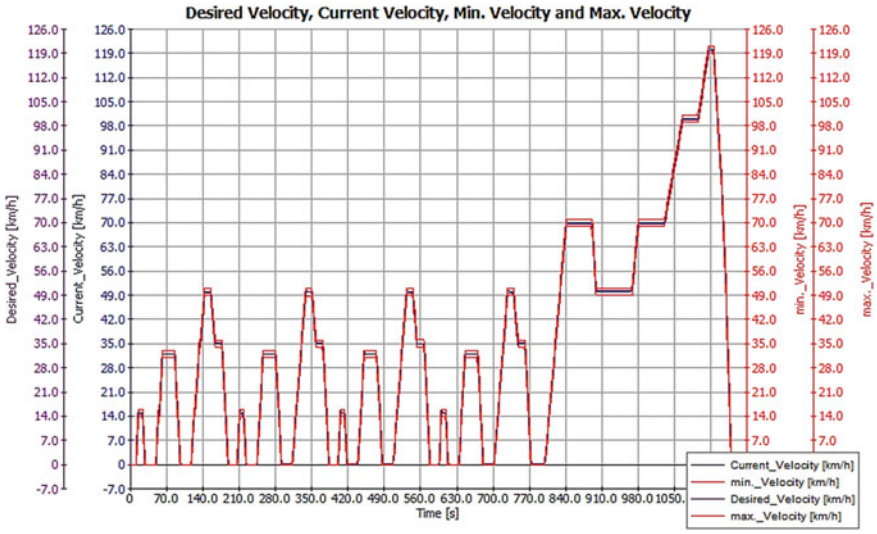


Fig. 6.110 Desired, current, minimum, and maximum velocity

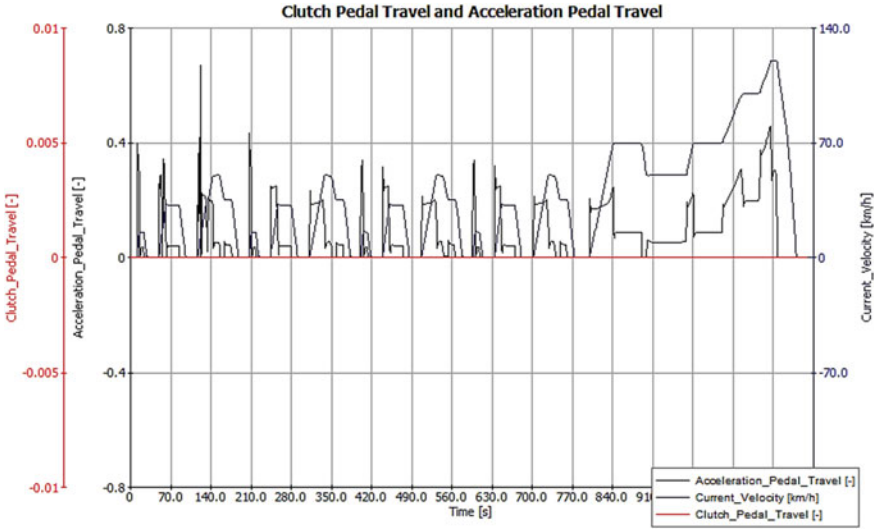


Fig. 6.111 Clutch pedal travel and acceleration pedal travel

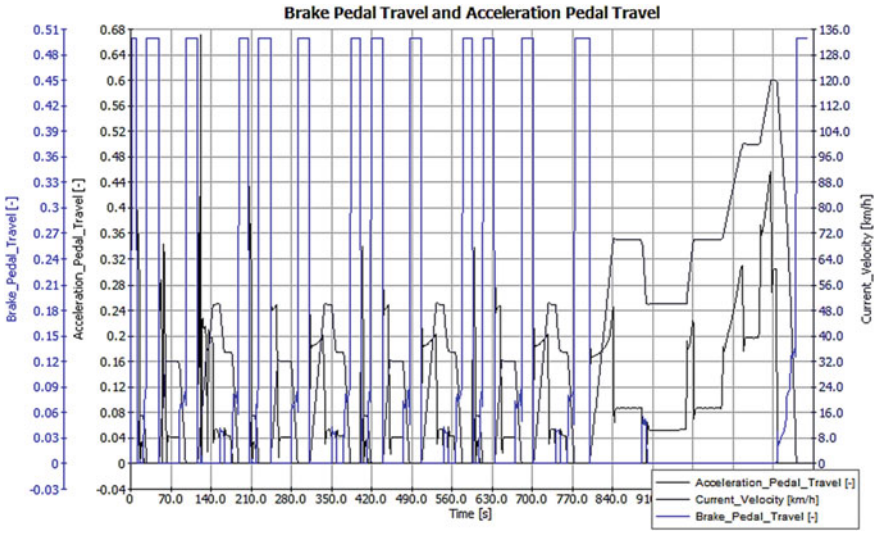


Fig. 6.112 Brake pedal travel and acceleration pedal travel

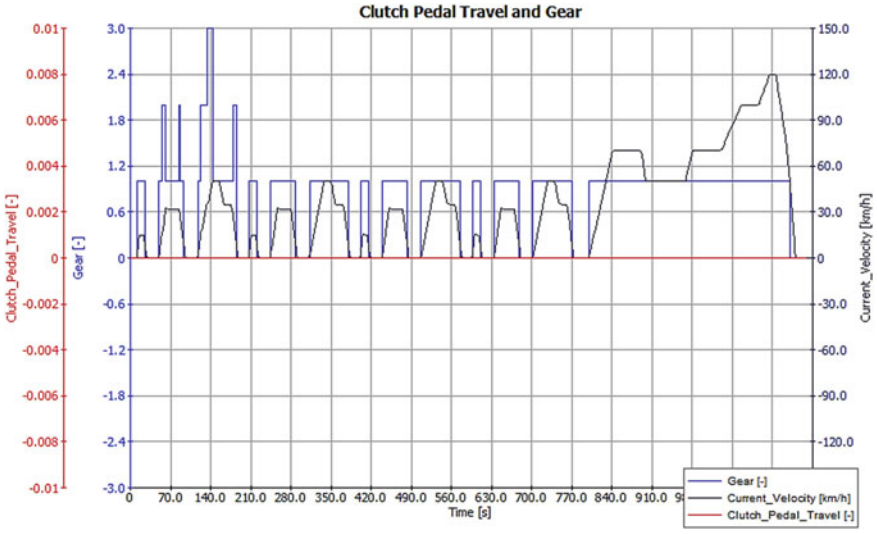


Fig. 6.113 Clutch pedal travel and gear

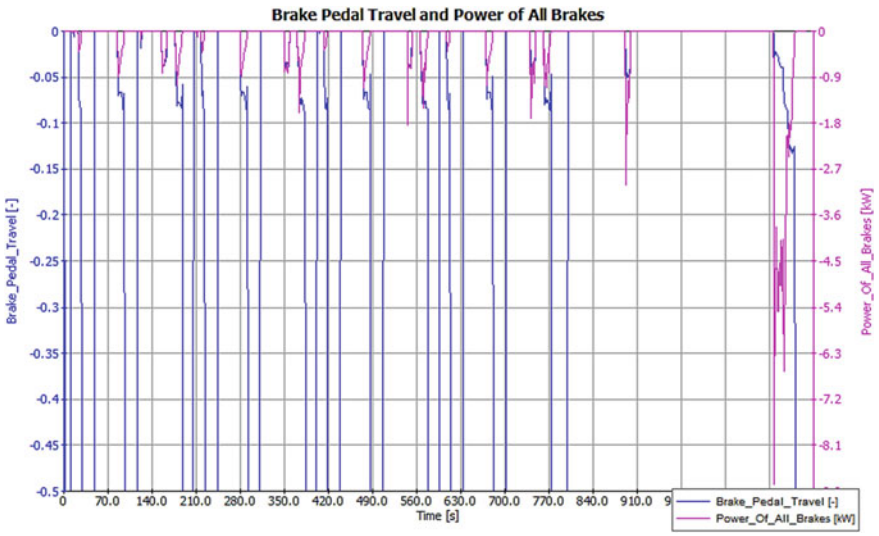


Fig. 6.114 Brake pedal travel and power of all brakes

References

1. AVL Cruise (2011) Users guide. AVL List GmbH, Graz, Austria, Document no. 04.0104.2011, Edition 06.2011
2. AVL Cruise (2011) Primer. AVL List GmbH, Graz, Austria, Document no. 04.0103.2011, Edition 06.2011

Chapter 7
Creating Virtual Road Infrastructure

7.1 AVL Road Importer

7.1.1 Getting Started

AVL Road Importer is an AVL Concerto™ option (Fig. 7.1). The purpose of this option is to convert any GPS data or x, y data of a real road into a format readable by AVL Concerto™ [1].

This tool is not a GIS tool in the sense that it does not permit to log GPS data nor does it have any link to any mapping tool. All the data are provided by the user.

Therefore, the generated road is representative of that data. The only given information about the road are the points, which the user can limit in case they cannot be done with the given set of parameters.

This subchapter describes the possibilities of AVL Road Importer as well as its intended use. To navigate, use the command bar available on the left part of the screen. It is composed of four sections:

Data—in this section, the user is able to either import GPX or KML files to AVL Concerto™ or simply choose a file in AVL Concerto™ Data Explorer;

Road—in this section, the user is able to choose what data to work with, but also prepare it before the main algorithm;

Plot—in this section, the user can find supplementary tools to verify the quality of the road just generated but also you will be able to specify additional elements such as speed limits;

Export—in this section, the user will find the necessary tools to export to AVL InMotion or AVL CRUISE format [1].

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_7

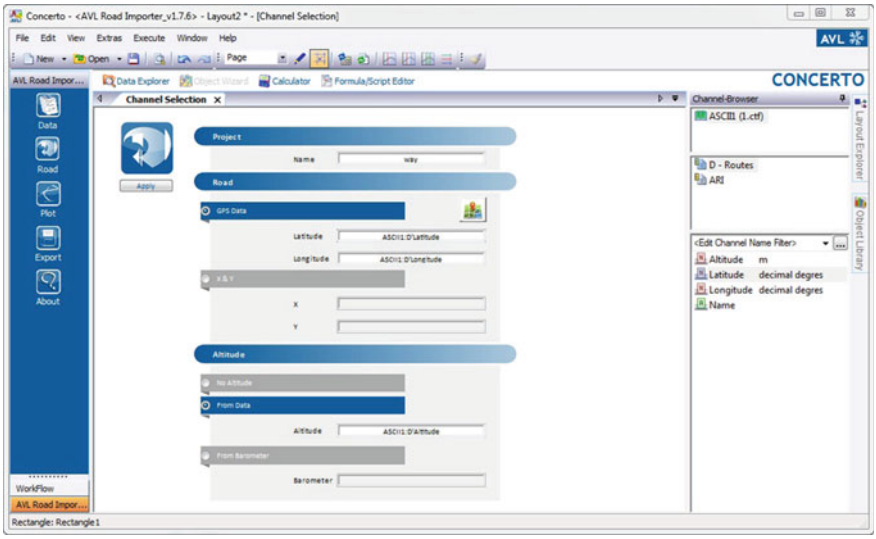


Fig. 7.1 AVL Road Importer main menu

7.1.2 Data Submenu

The Data submenu is accessible by clicking on the button Data in the command bar. In the submenu there are the following possibilities (Fig. 7.2):

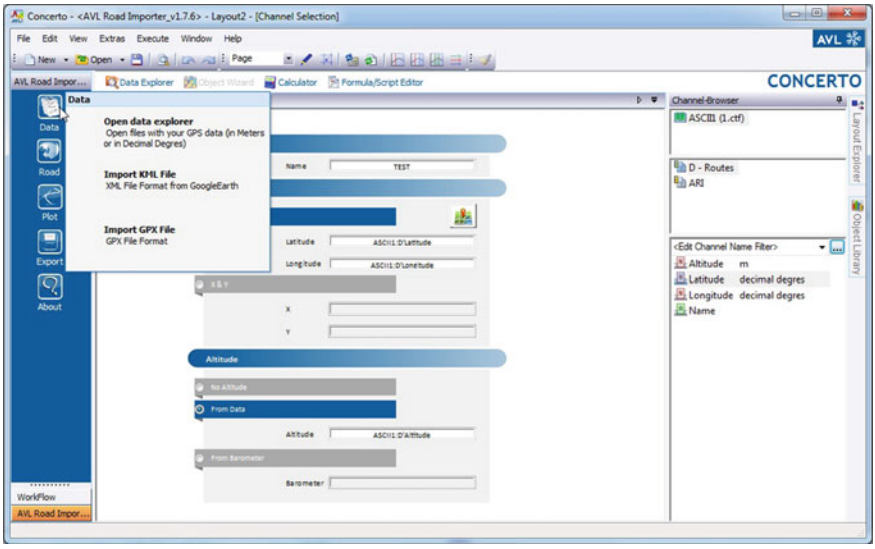


Fig. 7.2 AVL Road Importer—Data submenu

Open Data Explorer—this opens the AVL Concerto™ Data Explorer and the user is able to access any AVL Concerto™ file (read). This is also where previously imported KML and GPX files can be accessed.

Import KML File—the user is able to import KML through this. (by choosing the KML files wish to import and click ok). KML (Keyhole Markup Language) is an XML language focused on geographic visualization, including annotation of maps and images. Geographic visualization includes not only the presentation of graphical data on the globe, but also control of the user's navigation in the sense of where to go and where to look. After importing a KML file, it will appear in the Channel-Browser. The imported files are saved to the directory/Roads/KML/as a Concerto Transport File (CTF).

Import GPX File—the user will be able to import GPX through this (by choosing the GPX files you wish to import and click ok). GPX (GPS eXchange Format) is a lightweight XML data format for interchange of GPS data (waypoints, routes, and tracks) between applications and web services on the Internet. After importing a GPX file, it will appear in the Channel-Browser. The imported files are saved to the directory/Roads/GPX/as a Concerto Transport File (CTF).

7.1.3 Road Submenu

The Road submenu is accessible by clicking on the button Road in the command bar. In the submenu the user will find the following possibilities (Fig. 7.3):

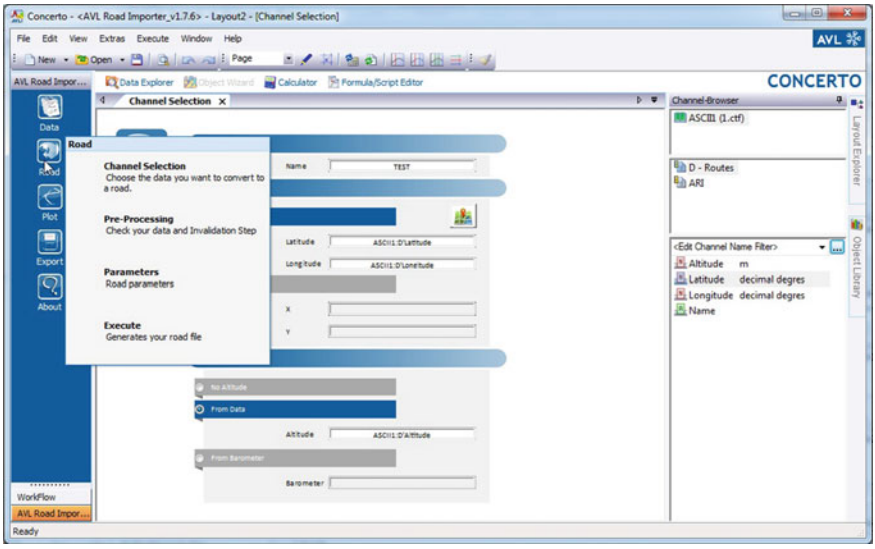


Fig. 7.3 AVL Road Importer—Road submenu

Channel Selection—by clicking on this button, the user can access the channel selection page (Fig. 7.4) [1]. Each modification of the parameters needs to be saved by clicking on the Apply button.

- Project—define the project name here. The project name in itself is not used by the algorithm but it helps predefine the name of the output files;
- Road—define which channel to use for either latitude or longitude or x and y. Each zone can be activated by checking the corresponding checkbox. If GPS data is specified, the algorithm will convert it into UTM coordinates;
- Altitude—defines which channel to use for the altitude. A channel can be chosen directly into (from data) or the channel containing the barometric pressure (from barometer). If the barometric pressure is chosen, the algorithm will convert the pressure into an altitude in meters.

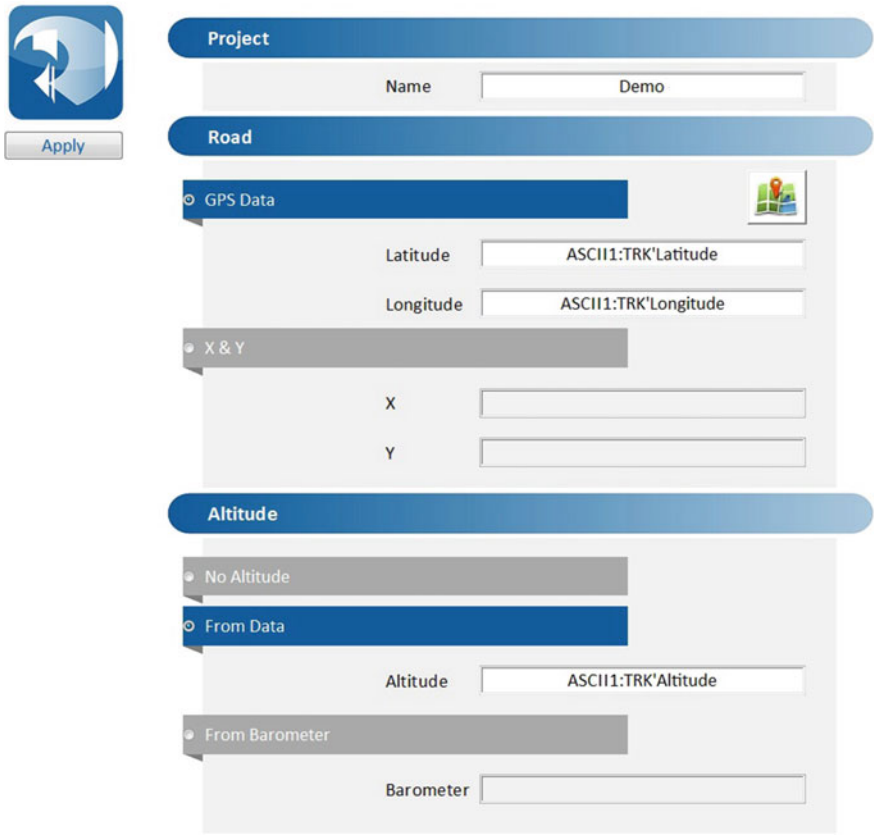


Fig. 7.4 AVL Road Importer—Channel selection

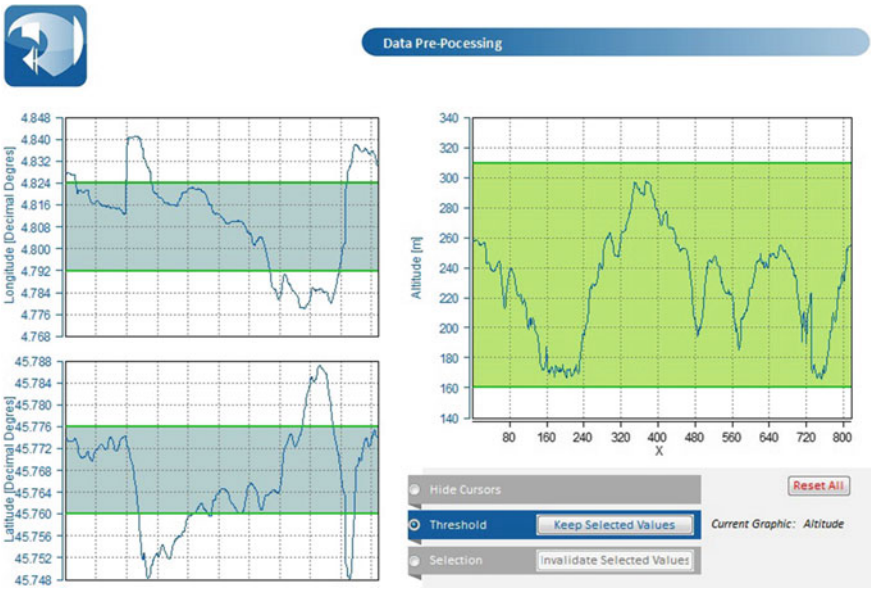


Fig. 7.5 AVL Road Importer—Pre-processing

Preprocessing—by clicking on this button, the pre-processing page is accessed (Fig. 7.5) [1]. This page serves two purposes:

- The first purpose is to be able to view quickly the selected data in the Channel Selection page;
- The second purpose is to declare invalid points in the data easily by selecting the part which is invalid with the available cursors.

Invalidating data will make the algorithm ignore those points for road creation.

Parameters—by clicking on this button, the parameters page is accessed (Fig. 7.6) [1]. Each modification of the parameters needs to be saved by clicking on the Apply button.

This page regroups all parameters for the main algorithm. It is cut down in several parts each regarding a certain aspect of the road.

- General—this section regroups all the general parameters for the road:
  i. Speed limits—define a default speed limit as well as the unit used for speeds;
  ii. Friction—defines a default friction between 0 and 1 for the entire road.

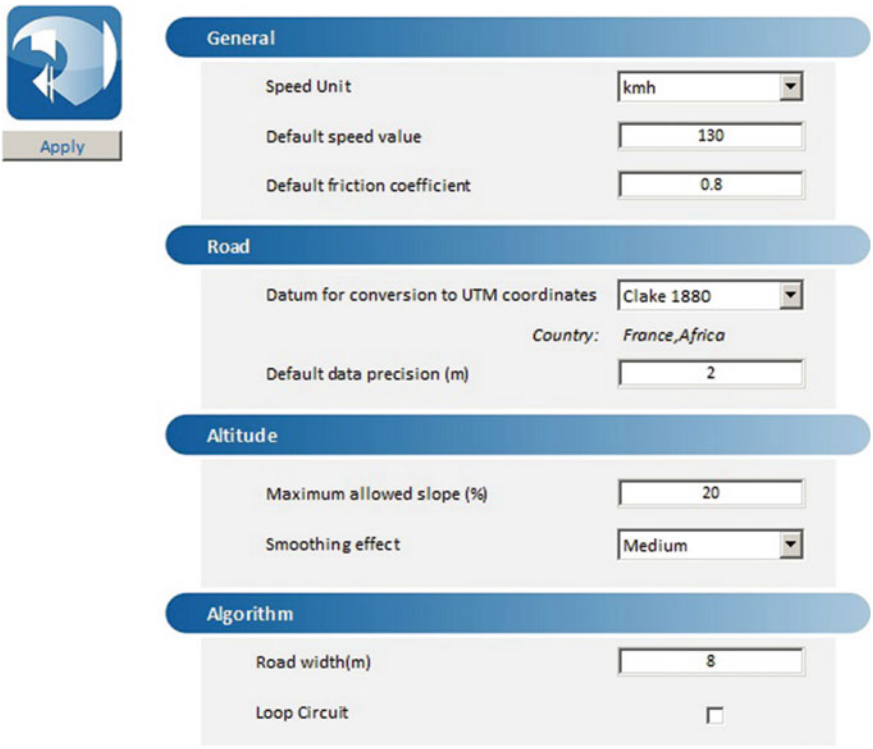


Fig. 7.6 AVL Road Importer—Parameters

- Road—this section regroups two options:
  i. Datum for conversion to UTM coordinates—you may choose the datum used to convert the GPS data. The datum has a different precision depending on the country;
  ii. Default data precision—this value allows the user to filter the data depending on the distance between two points. If this value is set to 5, it will only keep points that are lower than 5 m apart and the minimum value is set to 0.1 m.
- Altitude—this section contains all options relative to the altitude:
  i. Maximum allowed slope—choose the datum used to convert the GPS data. The datum has a different precision depending on the country;
  ii. Smoothing effect—this defines the applied smoothing to altitude. The used algorithm is a moving average. If None is set, no smoothing is applied. If low, medium, or strong is set the moving average applied once, twice, or three times respectively.

- Algorithm—this section contains all options that only concern the algorithm:
  i. Road width—this is the only parameter defining the road. This value is used to determine if the points will be removed or not depending on if the turn is doable. The larger the value the harder it is to make the turn, hence more values will be removed from the data.
  ii. Loop circuit—this parameter is still experimental. It enables the creation of a closed track. Activating this option will not only reconnect the endpoint to the first point but it will also try to correct the altitude to fully connect the three dimensions of the road.

Execute—this is how to start the algorithm. Depending on the file size this step may take some time. Once the algorithm finishes a file appears in the data explorer (Fig. 7.7) [1]. This file should contain:

- The original data in the measurement key O;
- The parameter used for the algorithm in the measurement key P;
- The results of the algorithm in the measurement key R.

To save this file, the user must right click on it and export it as a CTF, ATF, or ATF-XML (Fig. 7.8).

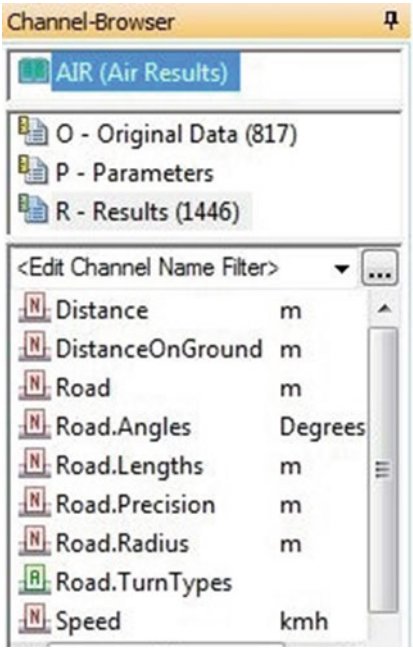


Fig. 7.7 Result file

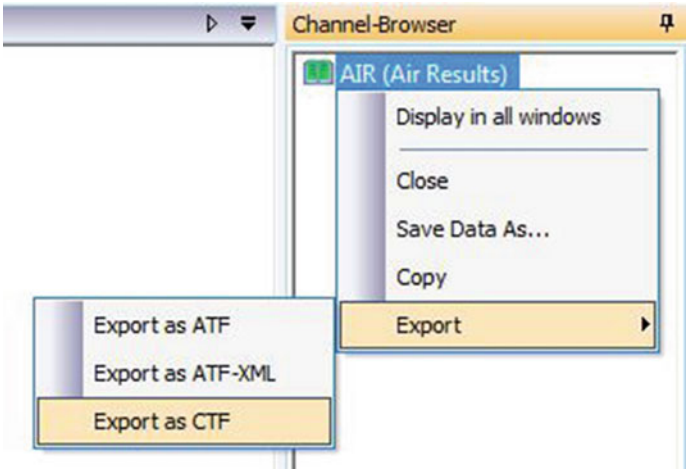


Fig. 7.8 Export the result file

7.1.4 Plot Submenu

The Plot submenu is accessible by clicking on the button Plot in the command bar. In the submenu there are the following possibilities (Fig. 7.9) [1].

- Elevation profile—clicking on this button, will access the elevation profile page (Fig. 7.10). The purpose of this page is to verify the quality of the altitude.

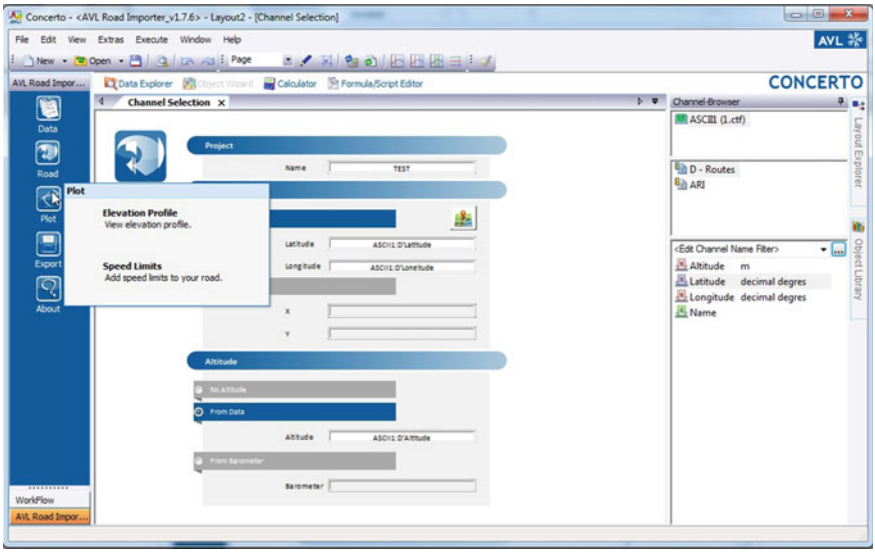


Fig. 7.9 AVL Road Importer—Plot submenu

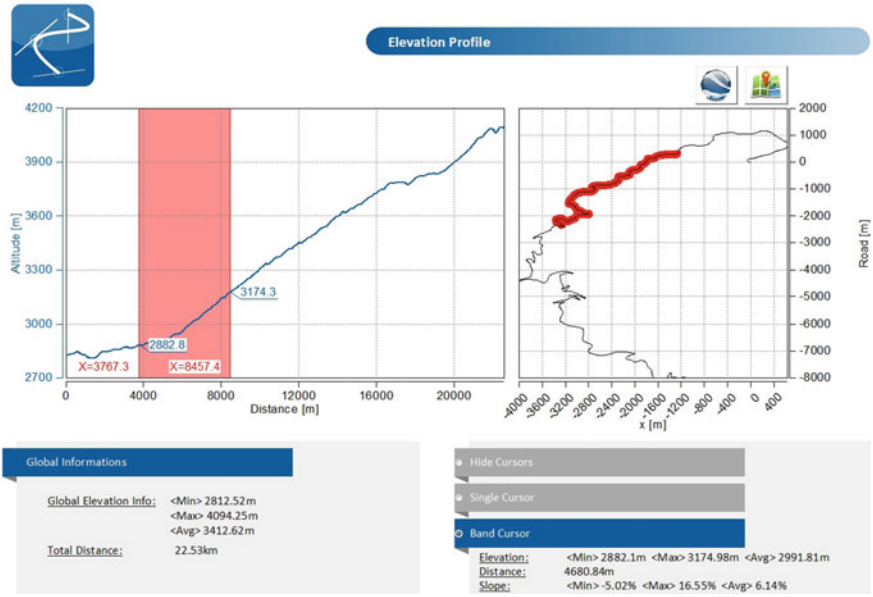


Fig. 7.10 Elevation profile

- Speed limits—by clicking this button, the speed limits page is accessed (Fig. 7.11). On this page, the specific speed limits for all parts of the road are defined.

The user can define the speed limits using the band cursor to select a portion of the road, and then click on a speed to be applied on this portion. By default the user may choose between 50, 70, 90, or 110 (km/h). The used unit is the one that the user specified in parameters submenu [1].

If the default values are not enough, the user can define own values in the textbox on the right and click on Apply.

The graphs on the bottom left of the page allow the user to see the set speed limits and it is updated every time a change is made.

The speed limits can be set up by automatic definition. In this section several methods are available to try and automatically define the speed limit based on the input vehicle speed coming from the data [1]. These methods are:

i. Method percentage—this algorithm will create speed limit zones based on the maximum vehicle speed witnessed in the data. Four zones will be identified as: 25, 50, 75, and 100 % of the maximum vehicle speed (Fig. 7.12);
ii. Method-specific country—this algorithm will determine the speed limits to apply based on the vehicle speed and thresholds defined by the user. To define the thresholds type them in the popup window (Fig. 7.13);
iii. Method max speed break down every X—this algorithm will determine the cut-off vehicle speed into zones depending on the distance traveled X where X



Fig. 7.11 Speed limits

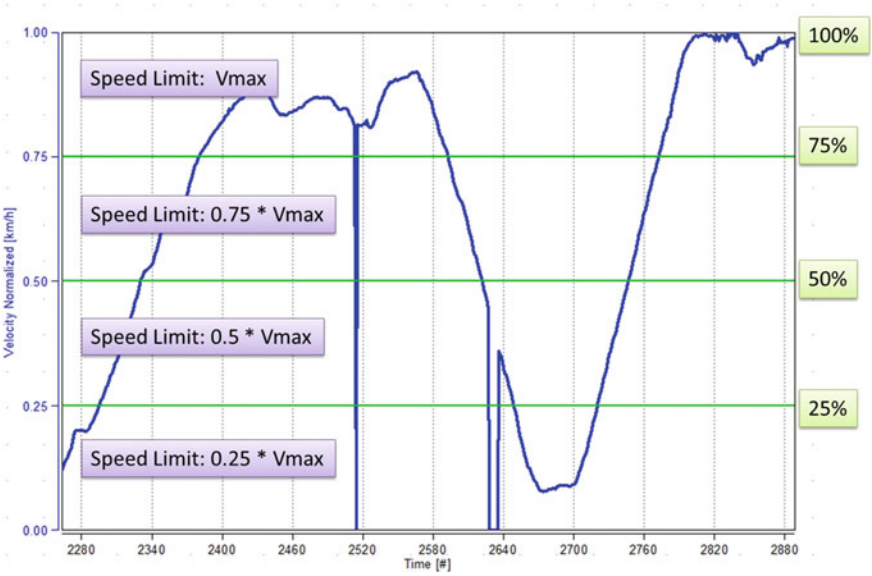


Fig. 7.12 Speed limits—Method percentage

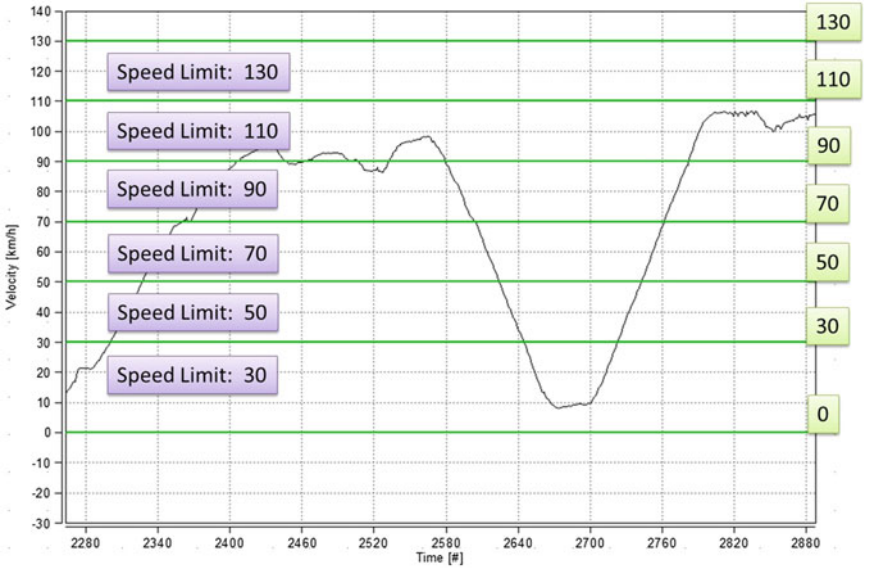


Fig. 7.13 Speed limits—Method specific country

can be either 5, 10, or 50 m. The algorithm will then apply the maximum of the vehicle speed in the defined zones as the speed limits for the road (Fig. 7.14).

For each algorithm above, there will be a detection of zero values for the vehicle speed. Every time a vehicle stop is detected there will be a stop panel added to the road automatically that will be the duration of the stop event.

7.1.5 Export Submenu

The Export submenu is accessible by clicking on the button Export in the command bar. In the submenu there are the following options (Fig. 7.15) [1].

- InMotion test run—when clicking on InMotion test run, the user will be prompted for a directory to save the test run. The extension is ROAD, and this test run only contains information linked to the road. It cannot be used as a standalone in InMotion. It can, however, be imported directly in the Road menu of InMotion. (this test run is not a digitalized road, the user has to import the road segments it contains);
- AVL CRUISE way file—when clicking on AVL CRUISE way file, the user will be prompted for a directory to save the way file. The extension is WAY, and this file contains only the altitude profile versus the distance for now.



Fig. 7.14 Speed limits—Method max speed breakdown every X

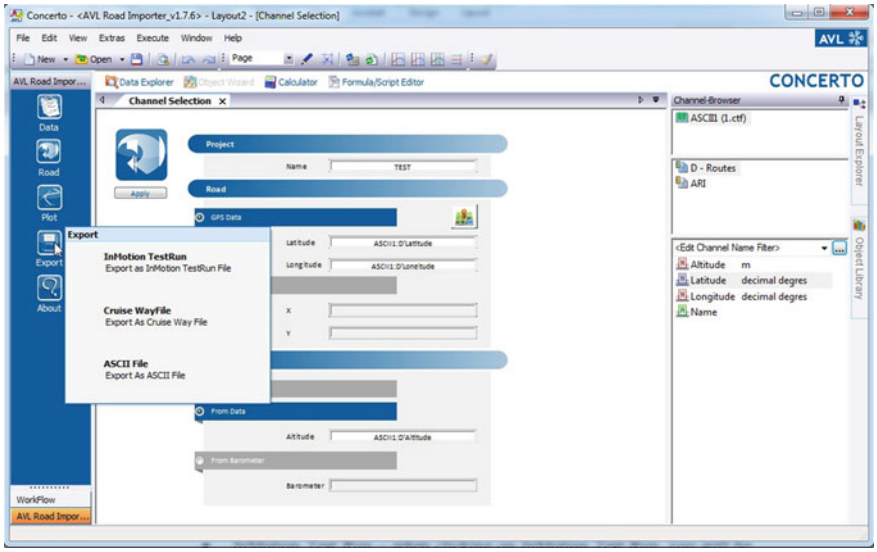


Fig. 7.15 AVL Road Importer—Export submenu

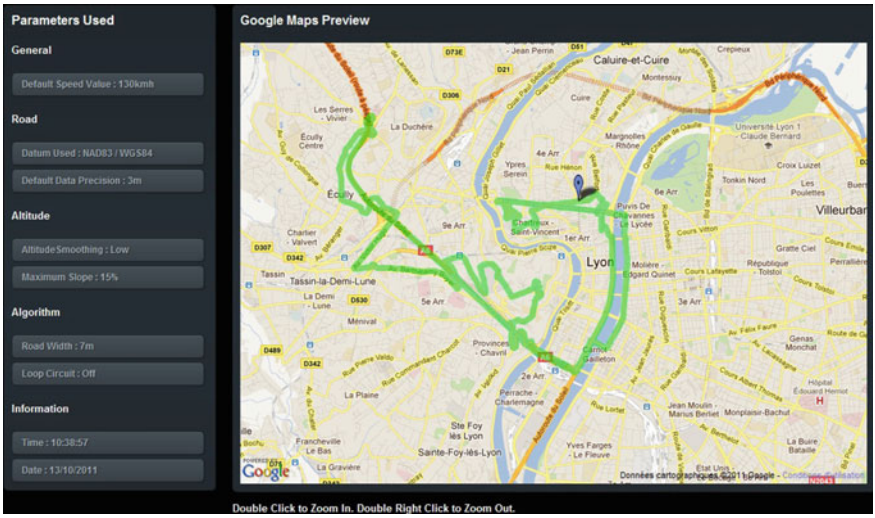


Fig. 7.16 HTML Google Map preview

- HTML Google Map preview—when the original data is in GPS coordinates (latitude, longitude) there is an HTML file generated automatically along with the AVL CRUISE way file or the InMotion test run. To view their content, they must be opened by using an Internet browser (Fig. 7.16).

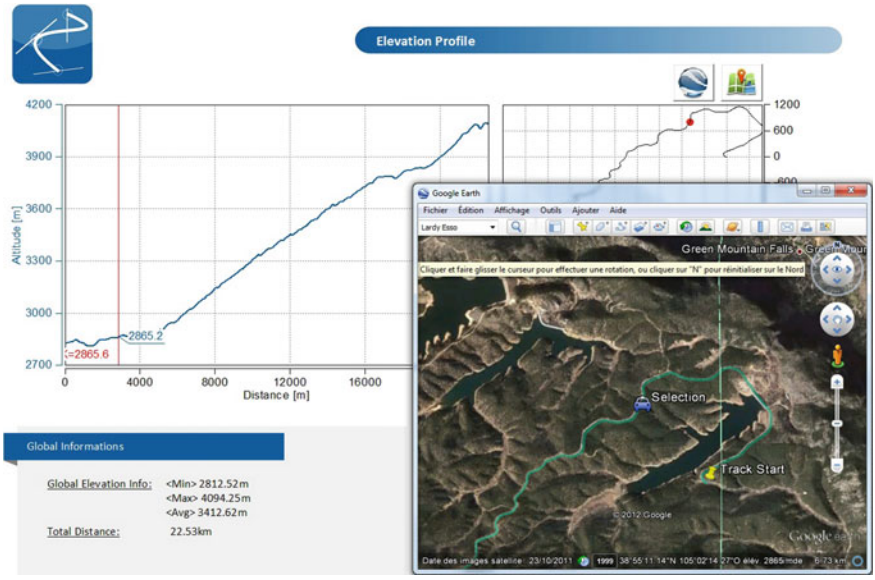


Fig. 7.17 Google Earth section

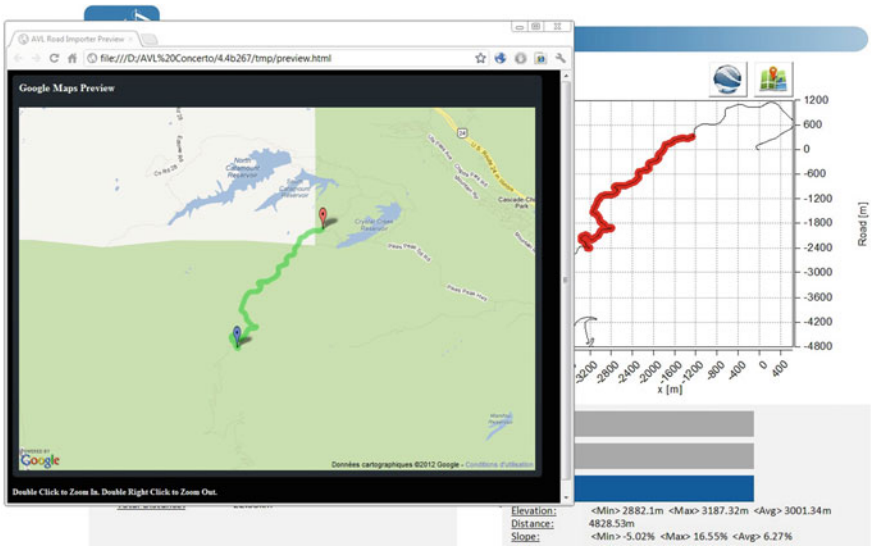


Fig. 7.18 Google Map section

7.1.6 Going Online

It is possible to go online to be able to visualize the data in a friendlier manner. Because Google Maps and Google Earth are great tools for this, AVL Road Importer will connect to this software to offer the best visual experience. Also, the user can go online and access those functionalities by clicking on the Google Earth and Google Maps buttons.

When clicking on the Google Earth button (Fig. 7.17), Google Earth will be opened and the data will be automatically displayed. There are two kinds of displays. The first is to display only one point at a time. This point will be represented as a car in Google Earth.

When clicking on the Google Maps button (Fig. 7.18), an Internet page will be automatically opened with a Google Maps display of your selection. Each click on this button will create a new Internet page.

Reference

1. AVL Road Importer (2013) User manual version 1.7, AVL France Technical Documentation

Chapter 8
Loop Powertrain Simulation

8.1 IPG CarMaker

8.1.1 Virtual Vehicle Environment

A virtual vehicle is a computer modeled representation of an actual vehicle with a behavior that matches that of its real world counterpart. With CarMaker, the virtual vehicle is made up of mathematical models that contain equations of motion or kinematics along with other mathematical formulas that define the multibody system. The model is parameterized with data that relates directly to the vehicle to be studied [1].

By this approach it is possible to use CarMaker to test any vehicle with a validated parameter set, and to easily switch between virtual vehicles by changing the parameter data that are used in the vehicle model. The virtual vehicle contains all parts of a real vehicle, including powertrain, tires, chassis, brakes, etc. It is also easy to integrate real automotive controllers (ABS, ESP, ACC) or software modeled controllers into the virtual vehicle by using hardware or software in the loop [2].

A virtual road is a digitized or computer-modeled representation of a road, track, or course which simulates a real course or one that is generated specifically for testing. With CarMaker, the road can be generated in two ways:

- By combining individual road segments, such as straights and curves, to form a larger road. For each road section there is a specific length, width, angle, slope, pitch, friction coefficient, etc., defined that can be specified;
- By using digitized data of an existing road that has been collected. With this approach, the measured data that are taken by survey or some other method is contained in a data file that is read by CarMaker and used as the road or a test track during simulation [2].

A virtual driver is computer software, which simulates the actions of a real driver. Everything that would normally be controlled by a real driver, such as turning the

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Green Energy and Technology, DOI 10.1007/978-3-319-18639-9_8

steering wheel, stepping on the gas, brake and clutch pedals, shifting gears in a manual transmission vehicle, etc., are controlled by the virtual driver. There are two approaches that can be taken into account to perform the driver actions:

- Simple control—with simple control, the actions are performed by specifying in advance what will happen at a certain time or distance;
- IPGDriver—the course is controlled by a smart computer driver, which tries to maintain a course on a test track and can also plan ahead. The driver can be modified to operate within specified limits. For example, a driver may have a fast or slow reaction time, he may want to maintain a certain speed, and he could be trying to go as fast as possible [3].

When the virtual vehicle, virtual road, and virtual driver are taken together, it can refer to it as the Virtual Vehicle Environment (VVE), since the virtual vehicle "drives" on the virtual road and is "driven" by the virtual driver (Fig. 8.1).

The CIT (CarMaker Interface Toolbox) consists of a number of tools (applications and utilities) that run on a host computer. The CIT includes the following:

- The CarMaker GUI—this is the main Graphical User Interface which is used to control the actions of the VVE, select the virtual vehicle parameter data, define or select the virtual road, set the virtual driver parameters, define or load maneuvers;
- The Vehicle Data Set Editor—edit any parameter of the vehicle with a convenient user interface. Each individual submodel class is editable in a separate tab;
- The IPGControl—visualization and analysis tools IPGControl can be used to view selected output quantities in real-time, load post-simulation data files, and plot and analyze the results;



Fig. 8.1 Virtual Vehicle Environment (VVE)

- The IPGMovie—real-time 3D animation of the VVE. The virtual vehicle is shown performing the specified driving maneuvers (performed by the virtual driver) on the virtual road;
- The Instruments—display the most important instruments, dials, and information about the vehicle driving conditions like: pedal position, steering wheel angle, gear selection, ignition, speedometer, tachometer, ESP and ABS warning lamps, brake light, etc.;
- DVA (Direct Variable Access) allow simulation quantities to be read and modified interactively through a user-friendly graphical interface;
- ScriptControl—test automation utility that allows scripts to be defined, edited, and executed. All the functions of the CIT can be controlled automatically using ScriptControl;
- TestManager—another utility for test automation. A mixture of script and GUI-based creation and execution of test series [2].

8.1.2 CarMaker Main GUI

To start CarMaker under windows press the Start button and select Programs—IPG—CarMaker.

The CarMaker main GUI pops up and automatically loads the project folders where the user was working before last shut down of the program. Nonetheless, it can easily switch the project folder by selecting File—Project Folder and select the one project for work [2].

The main window of CarMaker is called the main Graphical User Interface GUI (Fig. 8.2).

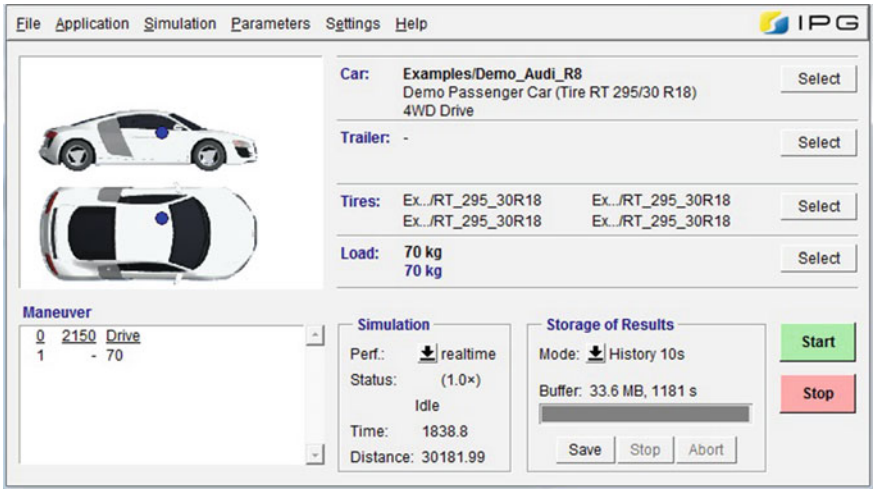


Fig. 8.2 Main GUI of CarMaker

Car subsections describe all parameters required to parameterize the vehicle model using the Vehicle Editor. In the excel tables by clicking once in a cell, their position can be moved to another cell by using the keyboard arrows [2].

The functionalities that can be found under file intend to manage the vehicle data set library. Below it can find functionalities that are available:

- To use a data set which is already built, corresponding vehicle file must be loaded via the vehicle editor;
- The user can also create a new vehicle data set from scratch. In this case, be aware that even if this option is chosen, the Vehicle Editor is filled with default values (the exception is the vehicle picture). If the vehicle parameterization not finished before closing, a comment should be added;
- Once the vehicle data set is parameterized, the changes can be saved or alternatively save them to a new file;
- Note that there is the possibility to import a part of the vehicle from another vehicle data set;
- The Vehicle Generator gives the possibility to generate a vehicle model with basic data only;
- The Vehicle Data Set Generator can generate a vehicle with basic data. This can be extremely useful if the work is dedicated on a new regulation system and on the exact vehicle parameterization itself [2].

Bodies are the masses of the vehicle models and can be described in the Vehicle Body tabs (Fig. 8.3) and Bodies (Fig. 8.4). According to the selected vehicle model (flexible or rigid), a different number of bodies can be parameterized. In case of a

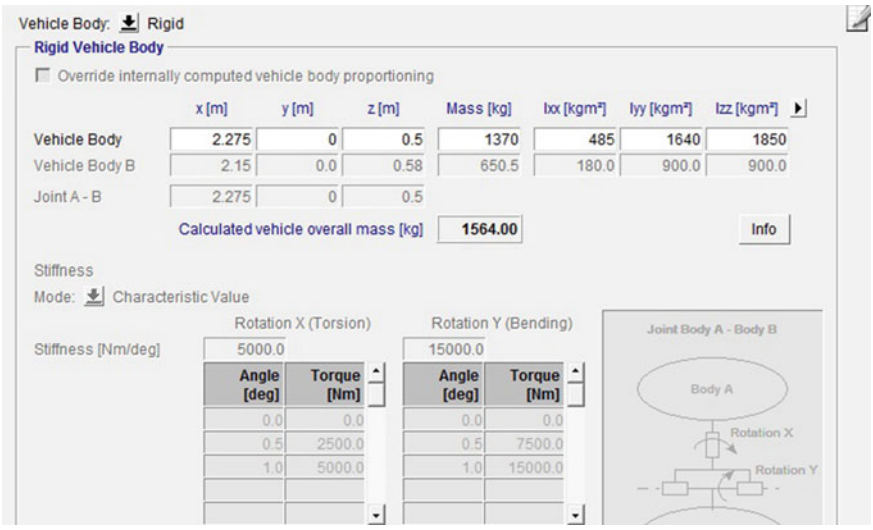


Fig. 8.3 Vehicle data set

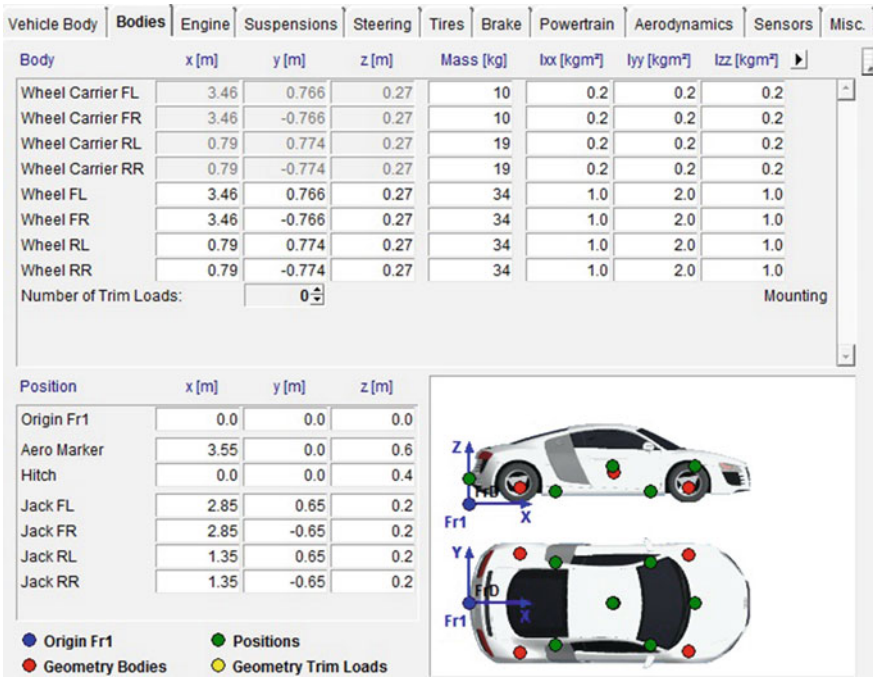


Fig. 8.4 Bodies

flexible body mode, the main body is split into two bodies. The main body/bodies include all sprung mass of the vehicle [4].

Engine Mount: CarMaker offers the possibility to simulate an elastically mounted engine. By activating this feature, an additional mass is added to the model which needs to be connected to the main body by a joint. The required settings can be specified in the Engine of the Vehicle Data Set Editor tab (Fig. 8.5).

The Engine Body is parameterized similar to the vehicle body. The position of the center of gravity in the design frame is required, as well as the moments and products of inertia [2].

Joint Engine section, the connection point from the engine mass to the vehicle body is specified. Mounting generalized Joint Force Mode, each of the five force elements Force X, Force Y, Force Z, Torque X, and Torque Y are made of a spring and damper element. The amplification factor can be used to easily manipulate the spring and damper characteristics by a multiplication factor given in this field.

The Characteristic Value description: the linear spring and damper characteristic defined by a single coefficient in (N/m) for the spring stiffness and in (Ns/m) for the damping.

1D look-up table description: nonlinear spring and damper characteristic defined by a look-up table. For the spring, the map requires the force in (N) over

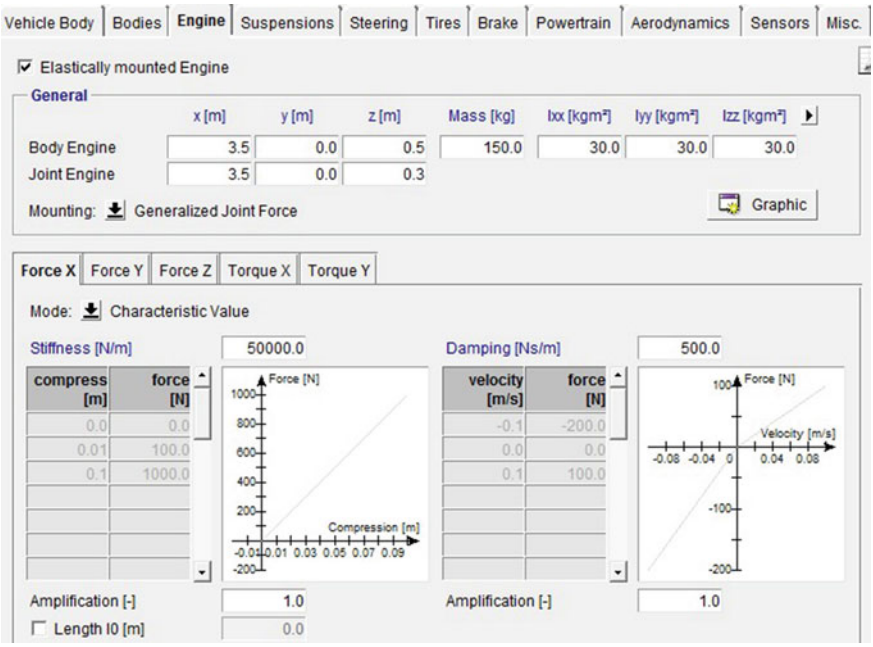


Fig. 8.5 Engine mount

compression in (m); the damper element is specified by force in (N) over velocity in (m/s).

Suspensions for a given axle: the spring characteristics are the same for both sides of the vehicle. The *Spring* is modeled as a component that generates a force when it is compressed or stretched (Fig. 8.6).

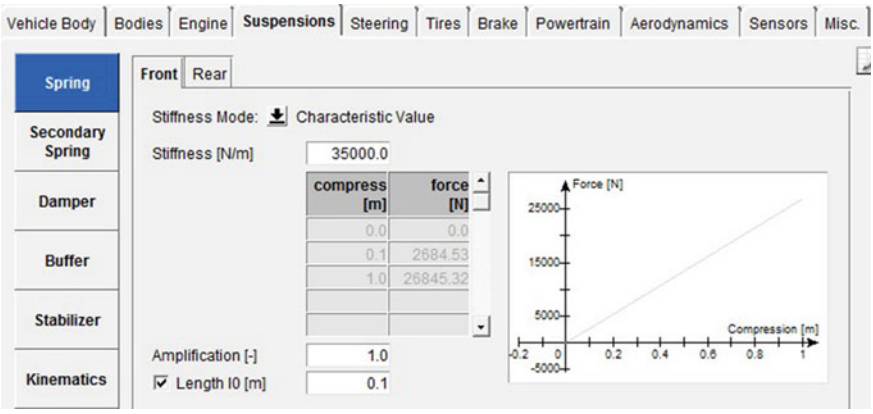


Fig. 8.6 Suspensions—spring

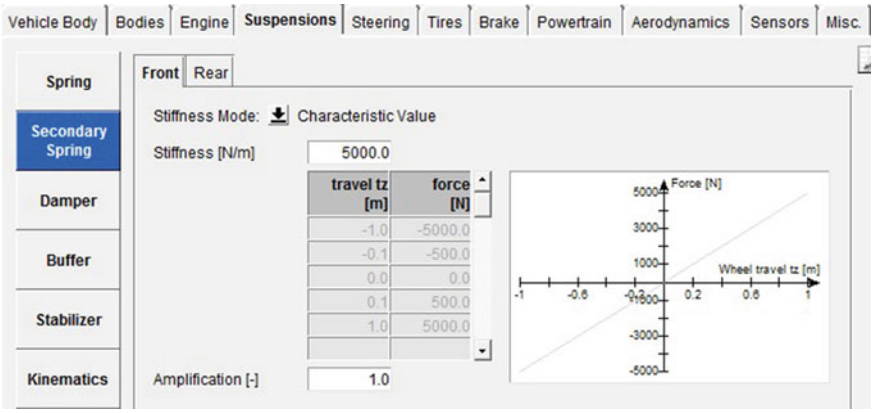


Fig. 8.7 Suspensions—secondary spring

For each front and rear axle, the stiffness of the *Secondary Spring* can be defined with a simple coefficient if the secondary spring force is a linear function of the wheel travel variation (Fig. 8.7). If the mode *not specified* is selected, the secondary spring is deactivated [2].

The stiffness parameter is either a simple coefficient or a table according to the selected parameter *Mode*.

Amplification parameter enables to scale the stiffness of the secondary spring very quickly for test purposes, instead of modifying the whole table. It can also use this parameter to convert the values to fit to the units required by CarMaker. The default value is 1.0. If the value is 0.0, the secondary spring is deactivated [2].

For a given axle, the *Damper* characteristics are the same for both sides of the vehicle (Fig. 8.8). The damper is modeled as a component that generates a force when being compressed or deflected (reaction to the change of velocity) [2].

For each front and rear axle, the damper characteristic is defined either by a coefficient or by a table of values according to the selected mode.

The characteristics of the damper are split into two domains: push and pull. For each domain a different damping can be defined. The push domain corresponds to a positive damper speed, which means that the damper is being compressed.

For a given axle, the *Buffer* characteristics are the same for both sides of the vehicle (Fig. 8.9). The buffers are used to limit the wheel travel in one direction or in both up and down. If the wheel traveled far enough to hit one of the buffers, the buffer acts like an additional spring [2].

That is why the user has to parameterize two buffers per axle (four in total), stiffness for each buffer, and the wheel travel from which the buffers are activated in both positive and negative directions.

The buffer stiffness can be parameterized by a coefficient (mode Characteristic Value) or by a table of values (mode look-up table 1D).

For each front and rear axle, the buffer stiffness are defined either by a coefficient or by a table of values according to the selected mode.

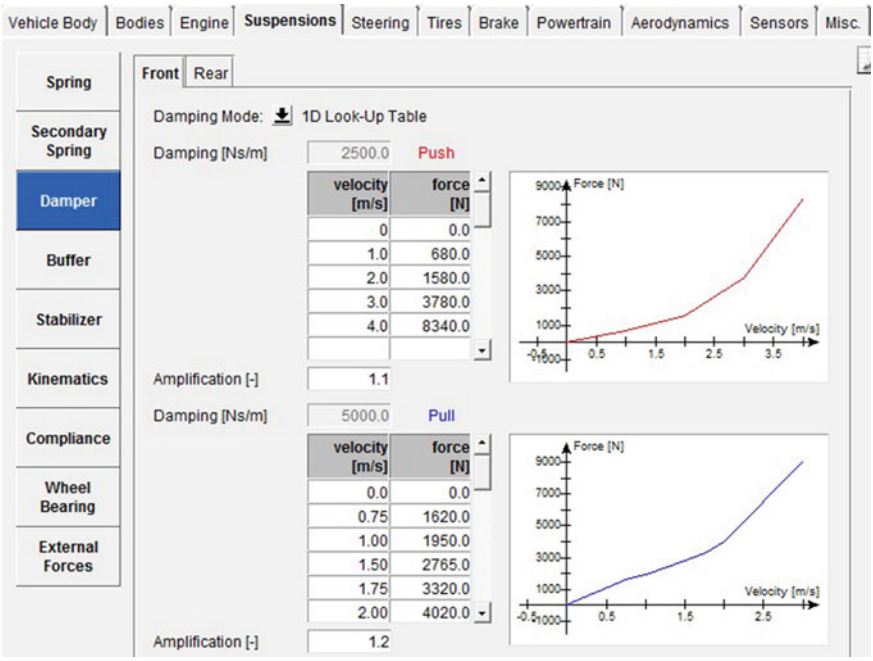


Fig. 8.8 Suspensions—damper

The characteristics of the buffer are split into two domains: push and pull, where the push domain corresponds to a positive wheel travel.

In the *Stabilizer* tab, only the properties of the single Anti Roll Bar (ARB) element are specified. Its angle or length variation is defined in the kinematics of the model [2].

Various *Kinematics* models are available (Fig. 8.10). The kinematics of the model has to be specified or each of the front and rear axles separately.

The *Compliance* model takes into account the transition of the wheel when forces are applied due to elasticity effects of the suspension (Fig. 8.11).

The user can choose between the following compliance descriptions that are available in the model option on the compliance tab, for others the user has to select the mode not specified and define them in an external kinematics file [2].

Wheel Bearing friction activates or deactivates the effect of friction at the wheel bearings. The wheel bearing friction is characterized by a single coefficient μ, which defines the friction force on the bearing. The bearing radius R enables to evaluate the friction torque on the bearing based on the friction force. Using the amplification factor *amp* the friction coefficient can be scaled very quickly instead of modifying the parameter itself [2].

External Forces are calculated by an external model and can be added to the spring, damper, or stabilizer forces calculated by CarMaker. The model can be generated by a C code or using MATLAB®/Simulink™.

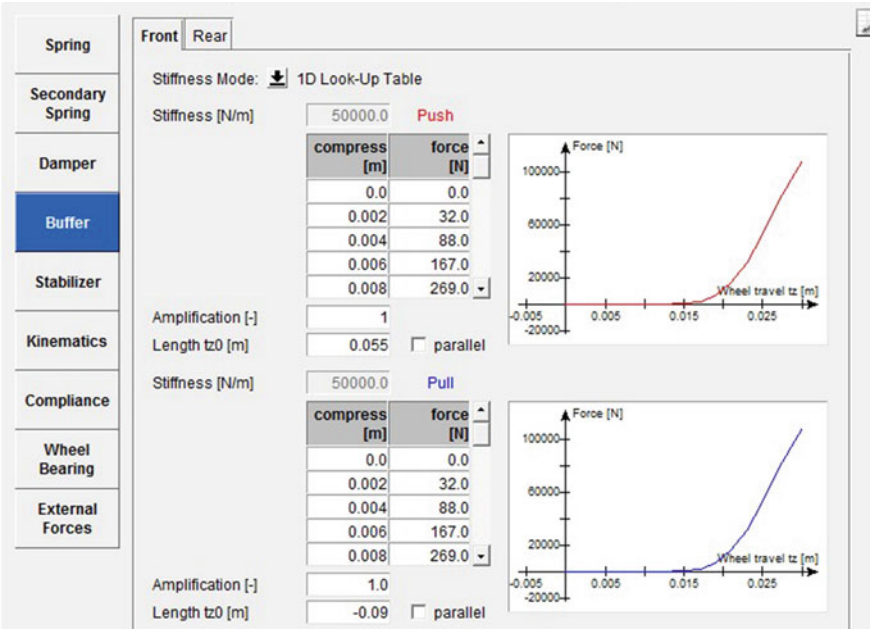


Fig. 8.9 Suspensions—buffer

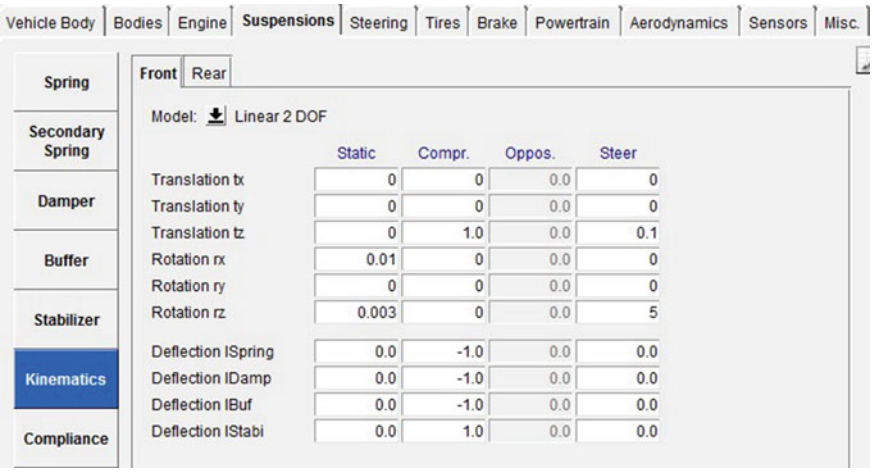


Fig. 8.10 Suspensions—kinematics

Steering System consists of a mechanical module which defines the ratio between the steering wheel angle and the steering rack displacement (Fig. 8.12). Optionally, a power steering unit can be added by selecting the *Pfeffer Steering model* which also regards friction losses in the steering system [2].

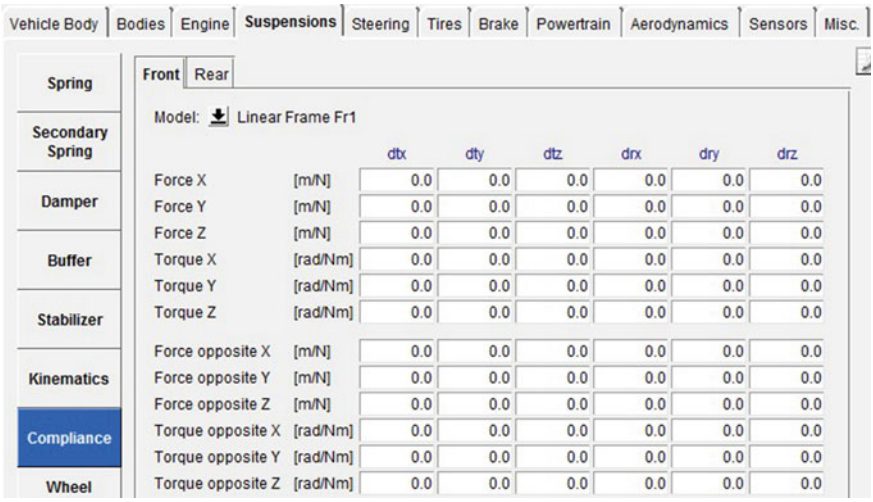


Fig. 8.11 Suspensions—compliance

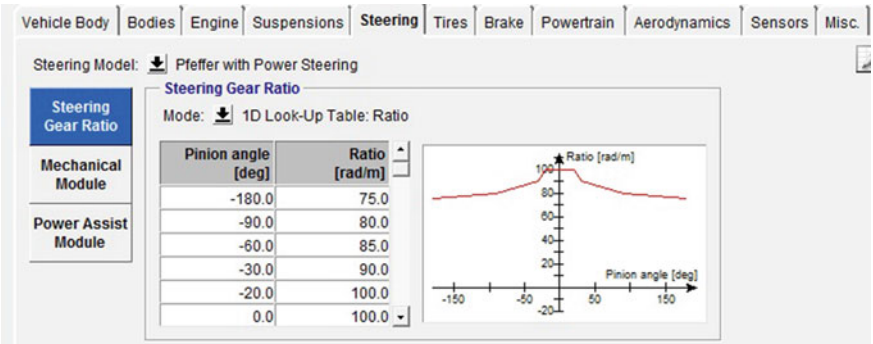


Fig. 8.12 Steering gear ratio

The Pfeffer Steering model is a very detailed model of a steering system including effects caused by friction losses, elasticity, and power steering.

The Mechanical module (Fig. 8.13) includes all mechanical components which transfer torque from the steering wheel to the tie rods.

The Power Assistance module can be of the following modes: hydraulic (HPS), electrical (EPSc and EPSapa), or user defined (Fig. 8.14).

Because the power steering is a high-frequency system, the calculation of all quantities once in the simulation cycle might not be sufficient to reach correct results. For this, the integration time can be enhanced to x-times of one simulation cycle using the option integration sub-steps [2].

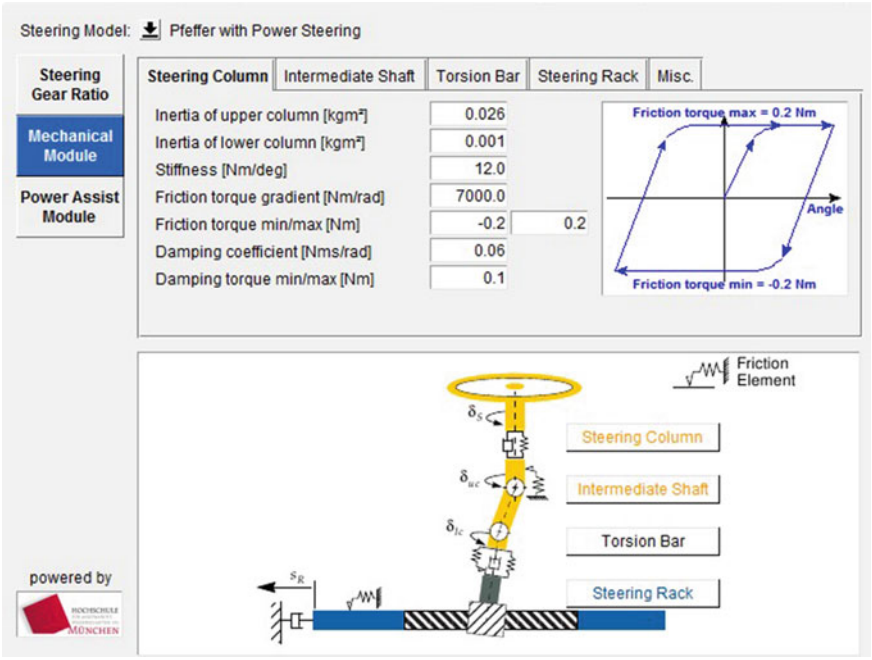


Fig. 8.13 Mechanical module

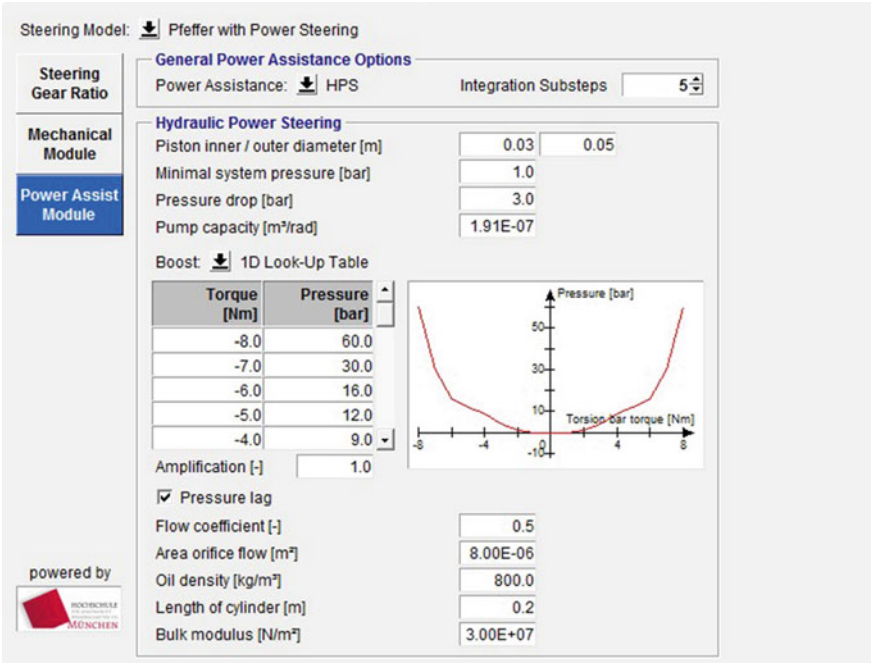


Fig. 8.14 Power assistance module

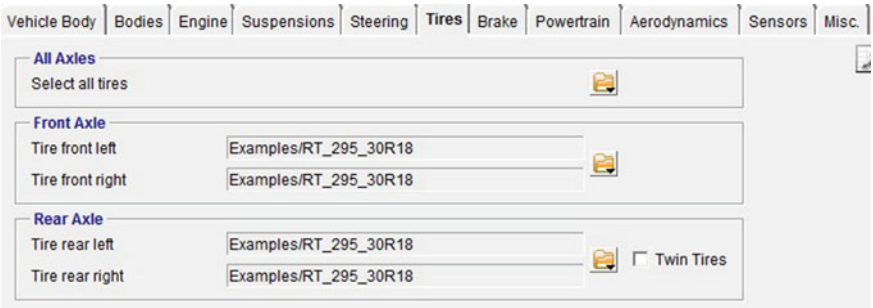


Fig. 8.15 Tires

The hydraulic power steering unit supports the steering wheel motion on the base of hydraulic pressure generated by an engine-driven pump.

Using the DVA mechanism the user can implement his own assistance model or a steering without assistance.

Tires are parametrized within the vehicle data set (Fig. 8.15). The purpose of the tire models is to calculate the slips and the stress applied to the contract point on the road (patch point) and then to convert them into stresses applied to the wheel center, since the rest of the vehicle model directly uses those efforts.

Brake model determines the ratio between the forces at the brake pedal to the braking torque at each wheel (Fig. 8.16). The brake system consists of hydraulic models and does not contain any controller model.

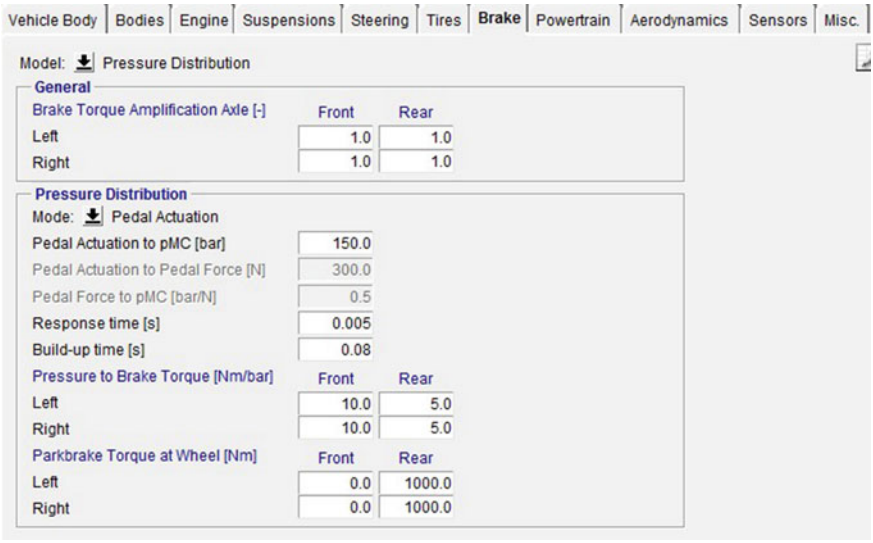


Fig. 8.16 Brake

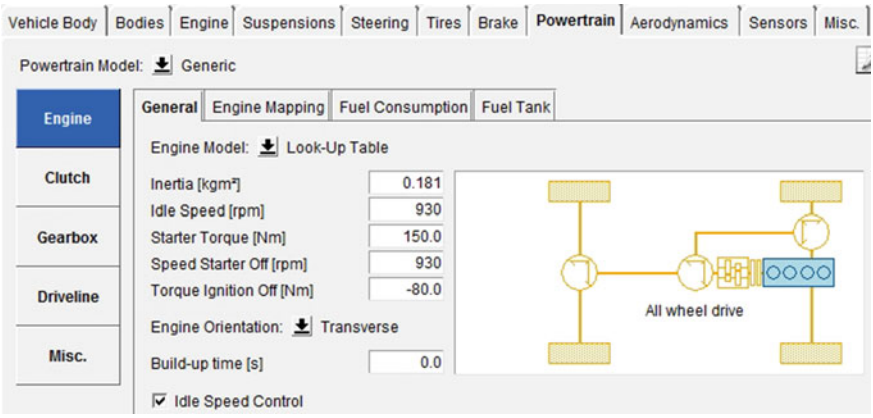


Fig. 8.17 Powertrain—general

Powertrain module is a torque transmission model which transfers a torque from the engine to the wheels. In reaction to that, the wheel speeds are modified and the rotation speed of the different components of the driveline are calculated subsequently (Fig. 8.17).

The engine is seen as a torque source producing its output depending on the throttle position and on its speed (its speed is imposed by the wheel speeds) [2].

The Generic Powertrain typically consists of the engine, the clutch, the gearbox and the driveline, which represents a classical powertrain with a combustion engine.

The way to parameterize the engine torque map is to use the engine mapping model look-up table 1D drag and full load (Fig. 8.18). The mapping model look-up

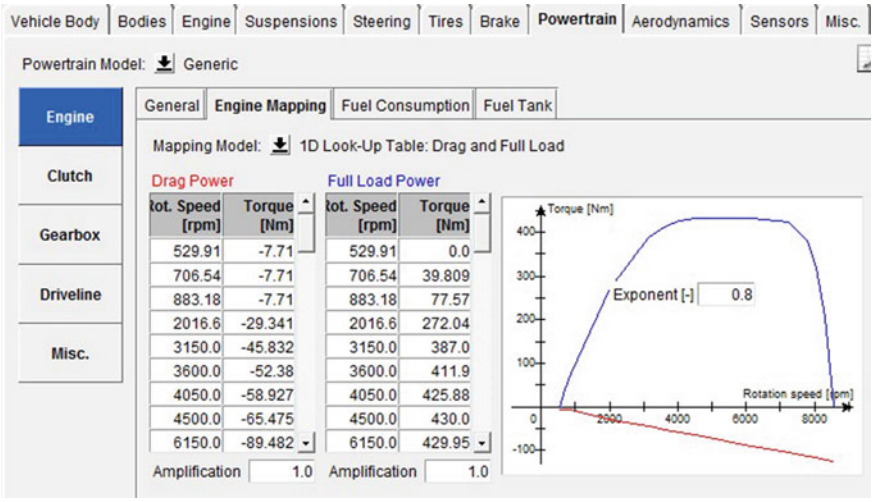


Fig. 8.18 Powertrain—engine mapping

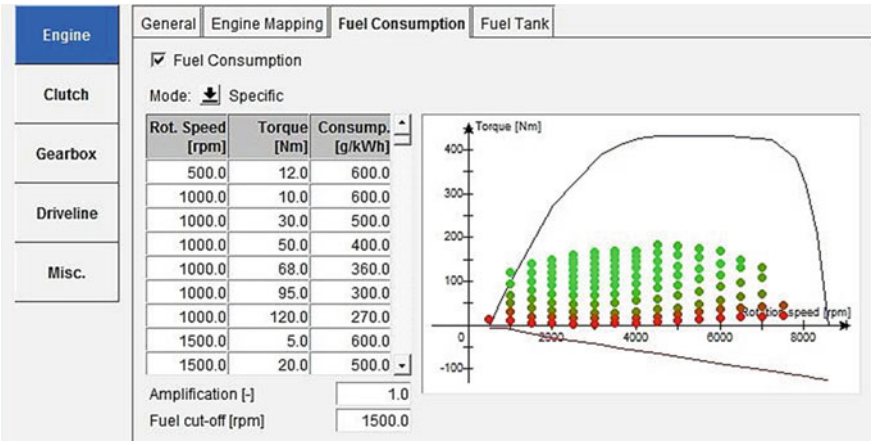


Fig. 8.19 Powertrain—Fuel Consumption Map

table 2D engine speed and gas may be used instead if the user wishes to define the torque values at mid-loads on his own. This is only necessary if you have a complete and accurate torque map of an engine and if the tests require a very accurate engine response [2].

For this model two characteristics have to be parameterized: the maximum engine torque and the drag torque characteristics (at a given speed the gas pedal is completely released). CarMaker interpolates the mid-load characteristics automatically, depending on the specified exponent.

A Fuel Consumption Map can only be added using the engine model look-up table (Fig. 8.19). Fuel tank parameters relating to the fuel and fuel tank can be carried out on this tab [2].

The Clutch model enables the transfer of all or none of the torque produced by the engine to the driveline part (Fig. 8.20).

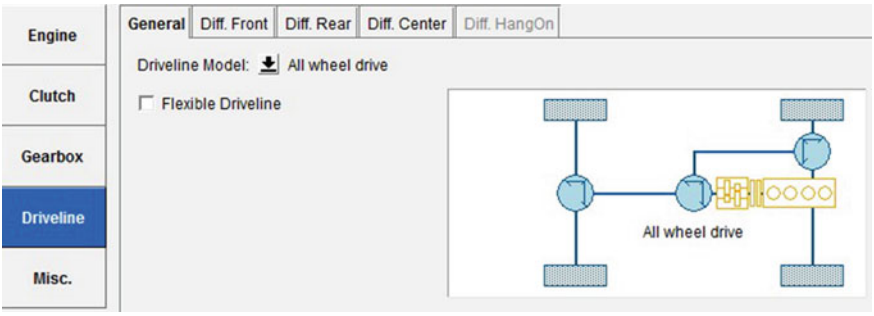


Fig. 8.20 Powertrain—clutch

The following clutch models are available:

- Friction model for a conventional mechanical clutch;
- Converter model for a vehicle equipped with an automatic transmission;
- DVA model where the user must define the torque transmitted by the DVA quantity.

The integrated lock-up table gives the possibility to define the speed at which the converter is locked or unlocked for each gear in dependence on the throttle position. The clutch is locked if the reference speed over-runs the lock speed limit and is unlocked if the gear number changes or the reference speed under-runs the unlock speed limit [2].

The gearbox module enables to convert the rotation speed of the shafts as well as the transferred torque just like a real gearbox would (Fig. 8.21).

For the automatic model an automated shifting unit can be modeled (Fig. 8.22).

With driveline models the user can choose the type of torque distribution (Fig. 8.23). The differential model transfers the torque from the input shaft to each wheel or for a differential to each axle. On the other hand the speeds coming from both output shafts are converted to a mid-speed imposed to the input shaft [2].

The differential models are exactly the same for the front and rear differential. Concerning the models for the center or hang-on differentials, only a few parameters differ from the other differential (Fig. 8.24).

When a wheel, respectively a shaft, is slipping, the differential is able to transfer a part of the torque to the wheel or shaft without slip, within a given limit.

The coupling model represents the differential models, which show how both output sides of the differential are linked together.

The aerodynamic model applies additional variable forces to the vehicle body, according to the vehicle speed. The adaptation of the map by accurate values is often not required as the aerodynamic model is of minor importance at low

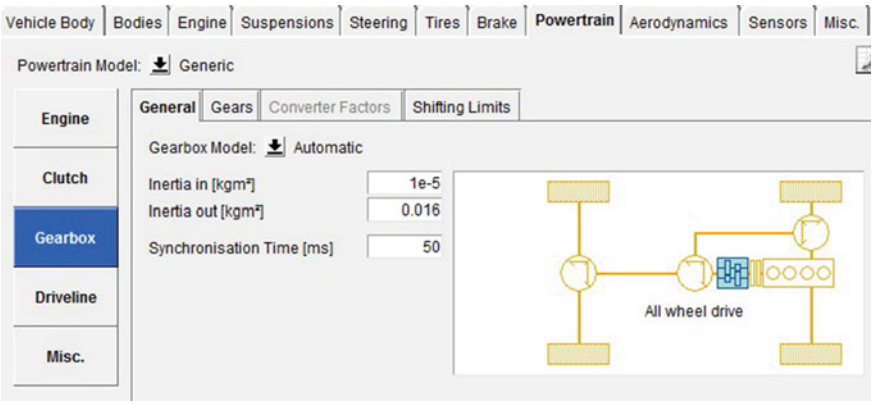


Fig. 8.21 Powertrain—gearbox

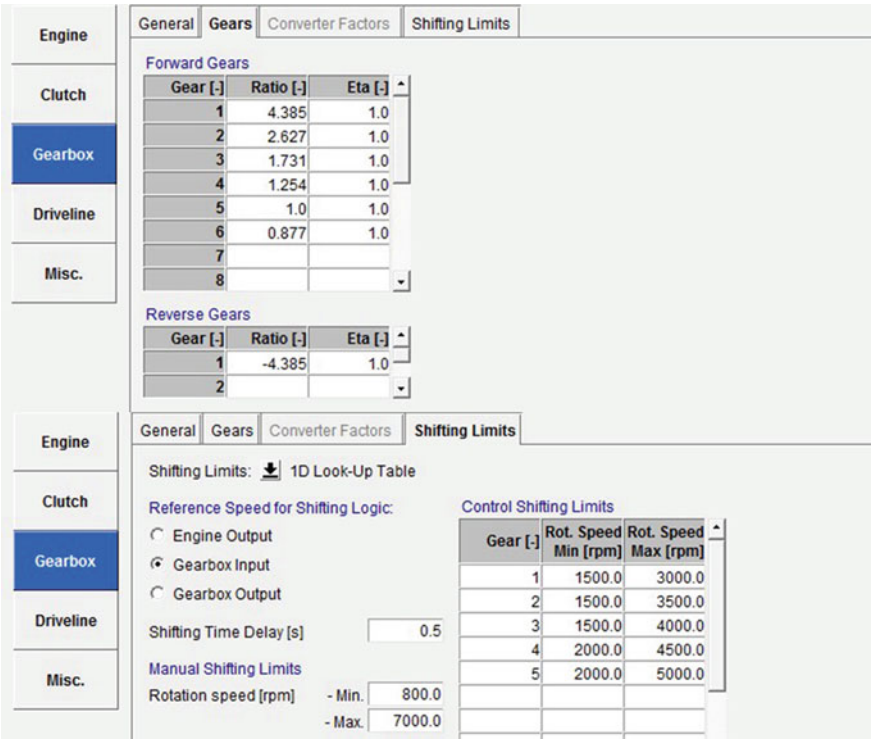


Fig. 8.22 Powertrain—gearbox automatic model (gears and shifting limits)

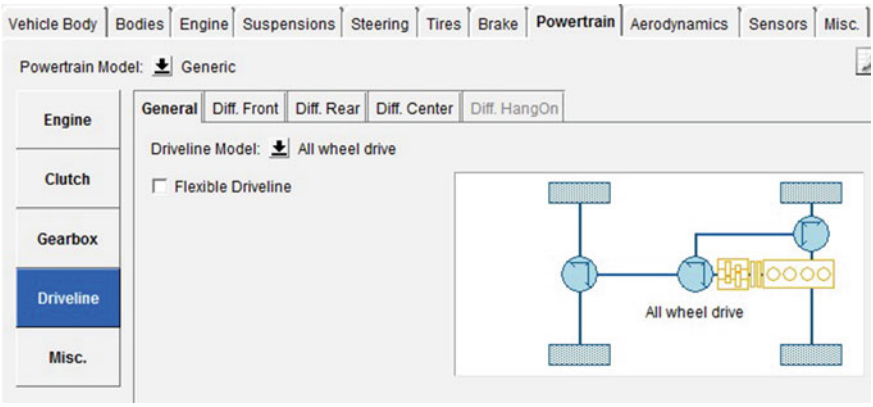


Fig. 8.23 Powertrain—driveline

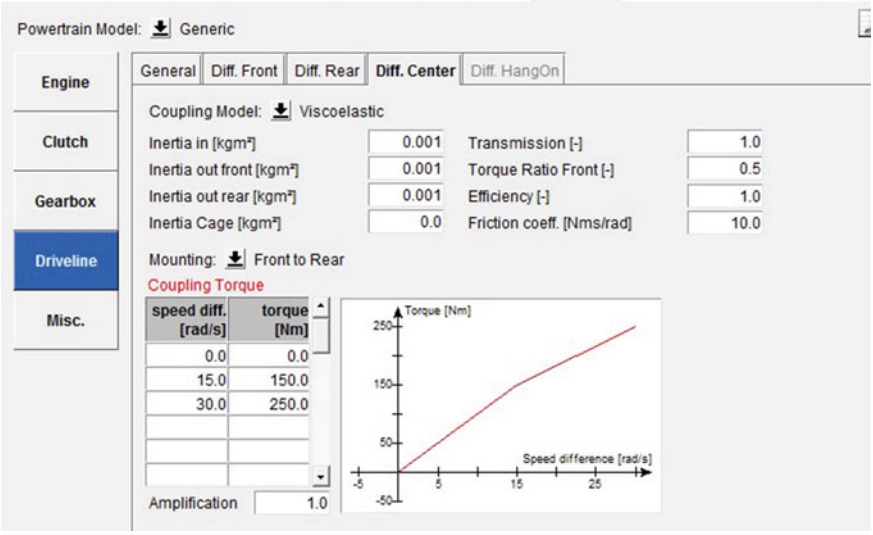


Fig. 8.24 Powertrain—driveline differential model

speeds [2]. Under about 100 km/h the influence of the aerodynamic forces is so small that the user can afford to leave the default values (Fig. 8.25).

In the Sensors tab, there is the possibility to define four types of sensors: Sideslip Angle Sensors, Body Sensors, Driving Assistance Sensors, and Road Property Sensors (Fig. 8.26).

Sideslip Angle Sensors are located in the vehicle center of gravity by default. A Body Sensor is an inertial sensor that can be positioned anywhere on the vehicle to measure the position, velocity, rotational velocity, acceleration and rotational acceleration. Up to 10 body sensors can be placed on the vehicle [2].

Driving Assistance Sensors (DASensor) can be parameterized independently, just by selecting the sensor in the general area. The parameters that are specific to the selected sensor are displayed under the graphical representation of the vehicle.

The Free Space Sensor Module (FSSensor) is an extended DASensor module, whose sensor beam is subdivided in equiangular horizontal and vertical segments.

The Traffic Sign Sensor (TSSensor) detects all or preselected traffic sign which falls within its defined range and horizontal/vertical aperture angles. The sensor cross-checks if the sign faces the sensor and then sorts all detected signs in ascending order with distance.

The Line Sensor module is used to detect lines and barriers that have been defined by the user on the road dialog using the road marking and/or traffic barrier options as a new bump or marker. It can be compared to an idealized camera.

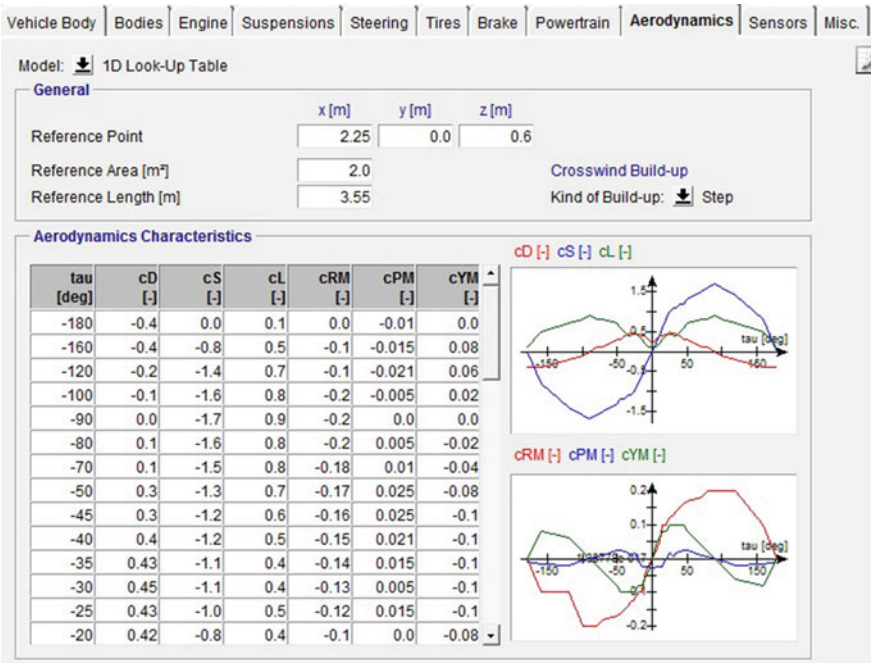


Fig. 8.25 Aerodynamic

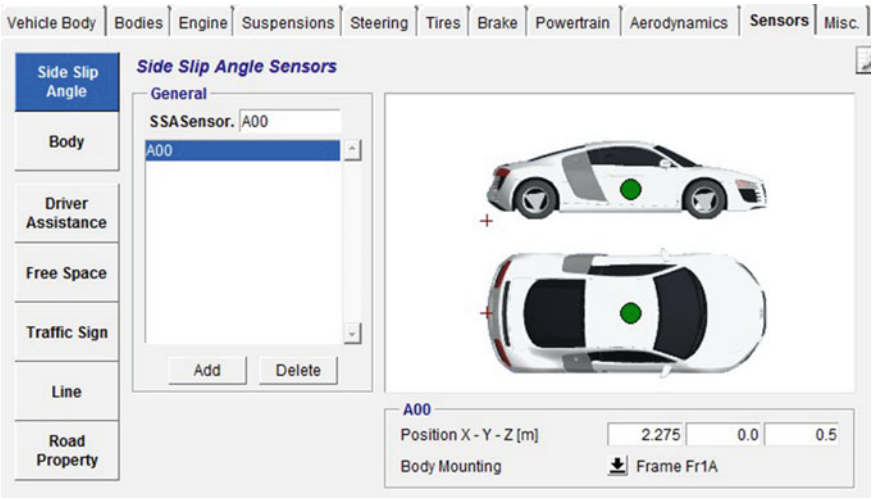


Fig. 8.26 Sensors

The Road Property Sensor collects road information at a user defined point ahead of the vehicle. Several attributes like the road bend and its deviation, road marker attributes (speed limit), or the longitudinal and lateral slope are detected.

This sensor can give information about the relative position: deviation distance, deviation angle, and current driving lane are calculated. This data can be important for various applications such as lane keeping assistance, lane departure warning, autonomous driving; sign detection, energy management, pre-scanning, and optimization of fuel consumption or detection of wheel lift [2].

In the Miscellaneous module the user can create his own vehicle graphics. Supported file types are PNG images (Fig. 8.27). Using PNG pictures, any photo can be imported.

A picture of the vehicle in top view and another one in side view is required. To create a PNG using IPGMovie, the picture needs to be scaled to the length of the vehicle (1 m = 100 pixel) and saved as a PNG image. Using the graphical tool, everything around the vehicle needs to be deleted to create a transparent background.

Then, select all and paste it to another file of the size of 560 × 226 pixels (72 dpi). Move the picture to the left side of the window (in case of a side view additionally align it vertically to the bottom). The top view should be saved in the same folder and finally the pictures can be selected in the CarMaker GUI [2].

Loads: The following section will present informations about the additional loads (Fig. 8.28). With the so-called trim loads there is the possibility to add some extra loads in order to simulate passengers, luggage, and heavy measurement equipment. Check if the static position of the vehicle using ModelCheck, the effects

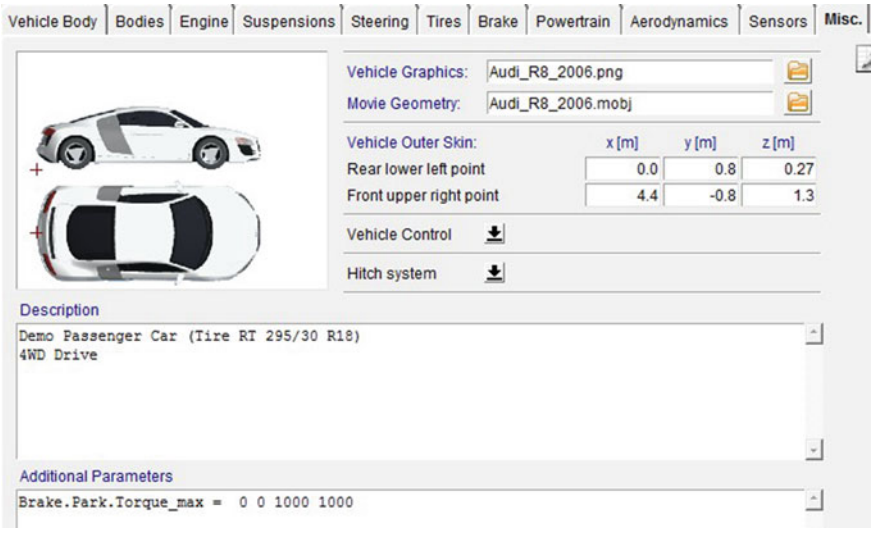


Fig. 8.27 Miscellaneous

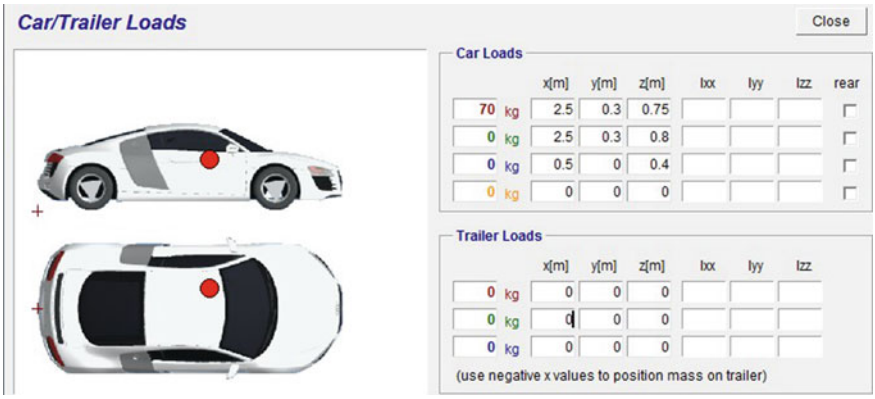


Fig. 8.28 Loads

of trim, loads will be included in the height of the vehicle's center of gravity or the wheel positions at the start of the configuration.

For some specific simulation purposes, the user may want to simulate a TestRun with an additional load on the vehicle, but still want to check the static state of the vehicle without it. The picture represents the vehicle body, defined loads (this is illustrated by a point) [2].

Maneuver is the concept of CarMaker for the driving scenario (Fig. 8.29) and it is following maneuver definition, which is split into several maneuver steps (acceleration, braking, etc.).

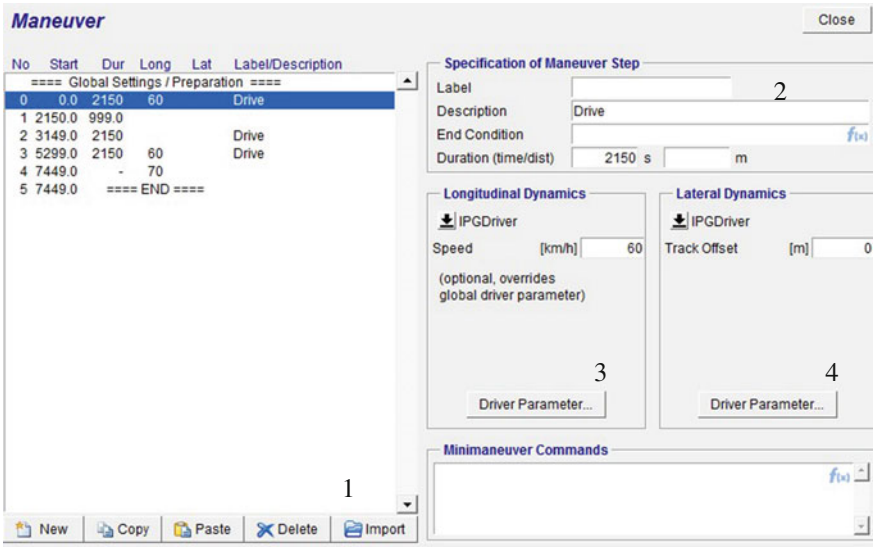


Fig. 8.29 Maneuver menu: *1* list of the maneuver steps, *2* specification of a maneuver step, *3* longitudinal dynamics, *4* lateral dynamics

These maneuver steps are called mini-maneuvers. Each mini-maneuver is composed of:

- Longitudinal dynamic actions: accelerating, braking, gear shifting, etc.;
- Lateral dynamic actions: steering;
- Additional actions, defined by a very easy script language.

CarMaker offers a convenient GUI to build a great diversity of driving scenarios. To build a driving scenario how to add and parameterize successive and various maneuver steps it is necessary to control the vehicle as the user wants. The list of the maneuvers steps is displayed and can be built in box 1.

The first entry in the maneuver list serves to specify starting conditions. Possible settings are the initial speed, the gear number, the steering wheel angle, and track offset.

A new maneuver step is added by using the *New* button at the bottom of box 1. The maneuver steps are always inserted ahead of the one selected. A maneuver step can be selected by clicking on the maneuver list in box 1; it is then highlighted in blue. To add a step to the end of the list, click on the entry " ==== END ==== " to select it, and then click on the *New* button.

Maneuver steps can also be copied and pasted, deleted, or imported from another TestRun. You can find the same functionality *Import* by clicking with the right mouse button anywhere in the Maneuver GUI [5].

After creating a maneuver step, the actions need to be defined. Each mini-maneuver consists of duration (box 2) and a description of the driver's task, separated in longitudinal and lateral dynamics (box 3 and 4).

On the specification of a maneuver step (box 2) the user can define an end condition for each maneuver step using real-time expressions. The classical end conditions—time or distance—can be directly entered in the duration fields.

Longitudinal dynamics (box 3) are available to fully automate and detailed speed and pedal control. To accelerate and brake the vehicle according to its dynamic limits, the option IPGDriver should be chosen (closed loop maneuver). This option activates the driver model for the longitudinal dynamics.

Possible specifications of lateral dynamics (box 4) are available to control the steering wheel [5].

Simulation the whole control of the VVE, and with this of the CarMaker simulation, is done via the CarMaker main GUI. The status of the simulation can be observed in the simulation box.

Storage of Results mode collects only selected data and it is temporarily stored in a ring buffer without being saved to the disk automatically. For mode saves all is selected, all data is continuously and automatically saved to the disk.

If one of the history modes is selected, the data is temporarily stored in a ring buffer. The saving process is started manually at the end of the simulation by clicking the Save button. The amount of saved data depends on the history mode that has been selected. If the mode history 10 s is selected, clicking on save at the end of the simulation will save simulation results for the last 10 s of the simulation [6].

8.1.3 CarMaker Main Parameters

IPGRoad, the road model of CarMaker, enables to calculate the position of any point on the road surface, including its coefficient of friction (Fig. 8.30). IPGRoad describes the centerline of the road (x, y, z), which is symbolized by the white stripes on the picture above.

Once the road geometry is defined, the track width counting from the centerline to both sides of the road has to be parameterized, too. The same goes for the friction coefficient of the road surface. In addition to that, it can redefine the width and friction coefficient only for a certain section of the road. Once the TestRun has started, the road definition is automatically linked to IPGMovie.

The IPGRoad dialog box can be accessed from the main GUI by selecting Parameters—Road. The first tab that appears shows the general settings of the road (Fig. 8.31). The global settings are [5]:

- Start coordinates x, y, z (m) defines the origin of the road;
- Start direction (deg) defines the angle offset from the first segment regarding the x-axis;
- Car starts at (m) define at which distance the car should start;
- Driving lane should be used: the left or the right one;
- Country is option for the visualization and availability of the traffic signs;
- Track width (m) is defined on both sides of the centerline;
- Margin width (m) the margins are basically longitudinal stripes on both sides of the entire road length;
- Friction stripe (m) in order to have a variable friction coefficient along the track width up to two stripes can be defined.

The definition of the road geometry with a segment-based approach consists of a succession of various segments (straight lines, curve left, or right) with correctly

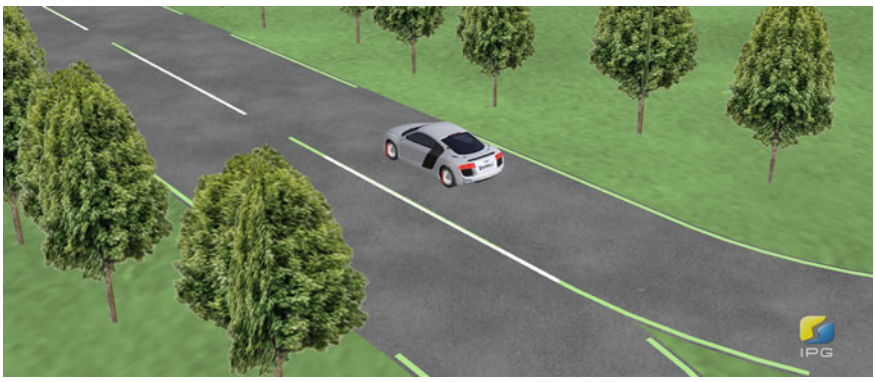


Fig. 8.30 Road in IPGMovie

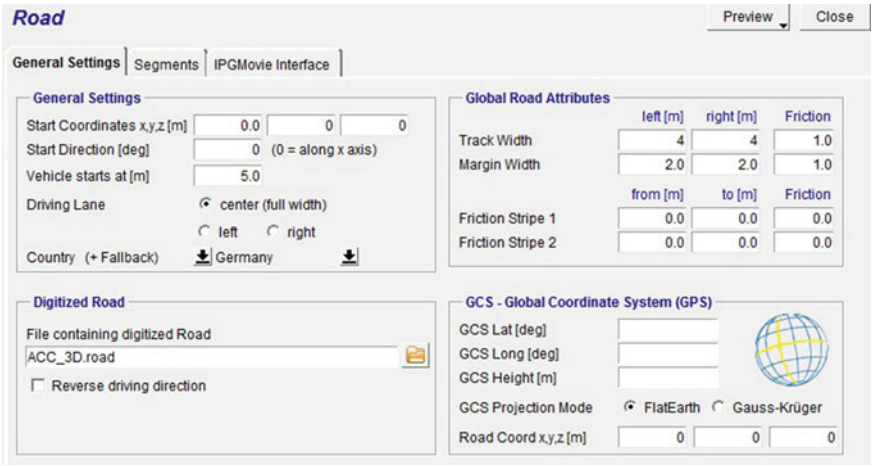


Fig. 8.31 Road—general settings

parameterized properties in order to build a complete road. To use this method, move to the second tab of the IPGRoad dialog box called *Segments* (Fig. 8.32).

To duplicate a segment, select the respective segment, click on "Copy", select the segment " ==== END ==== ", and finally click on the button "Insert" [7].

The segment list is displayed and can be built in the box at the bottom left of the road GUI. At this point, segments can be added or deleted. Once the geometry of

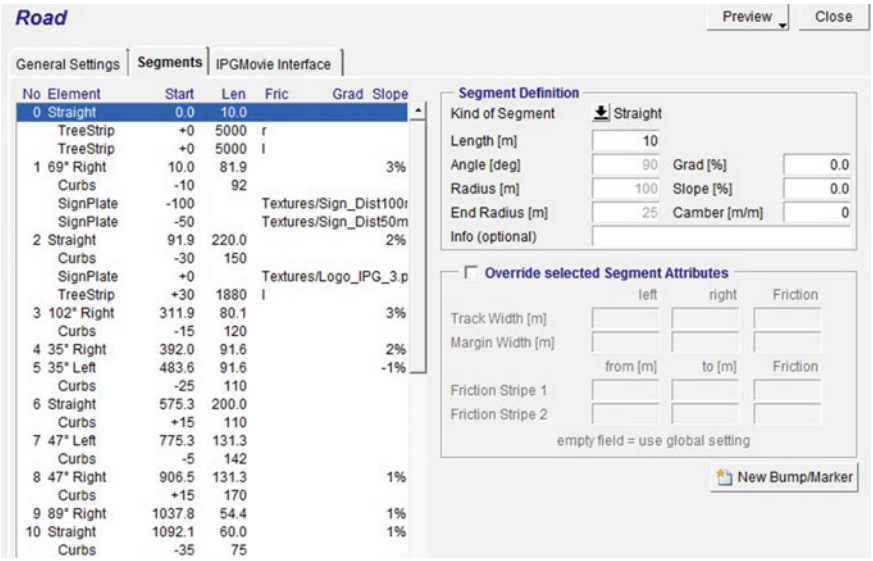


Fig. 8.32 Road—segments

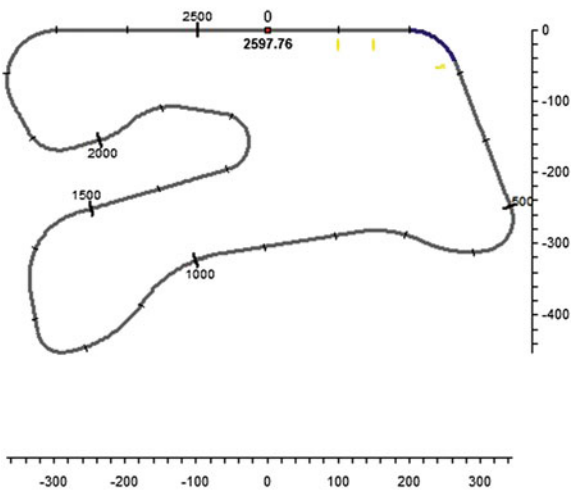


Fig. 8.33 Road—Bird's-Eye view

the road is defined either using digitized road data or the segment-based approach the user can check it with the Bird's-Eye view (Fig. 8.33).

An IPGMovie interface tab in the road dialog defines a road in terms of segments, bumps, markers, vehicle start position, etc. (Fig. 8.34).

CarMaker offers the possibility to use real measurements to define the maneuvers (Fig. 8.35).

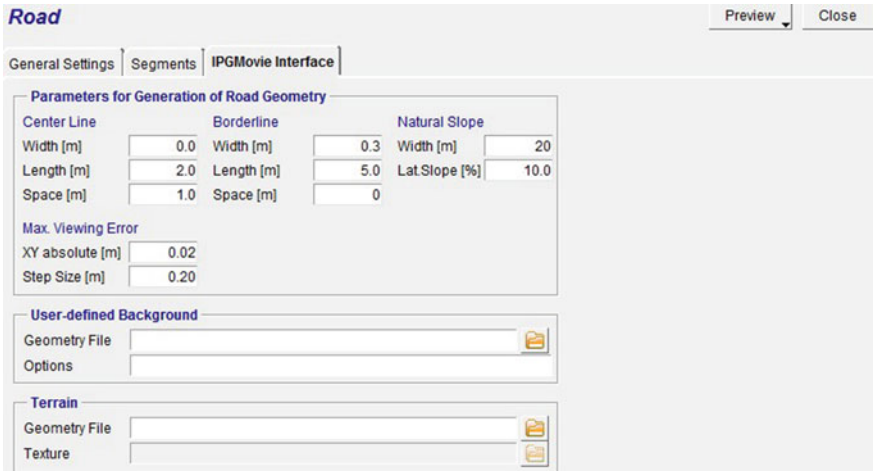


Fig. 8.34 Road—IPGMovie interface

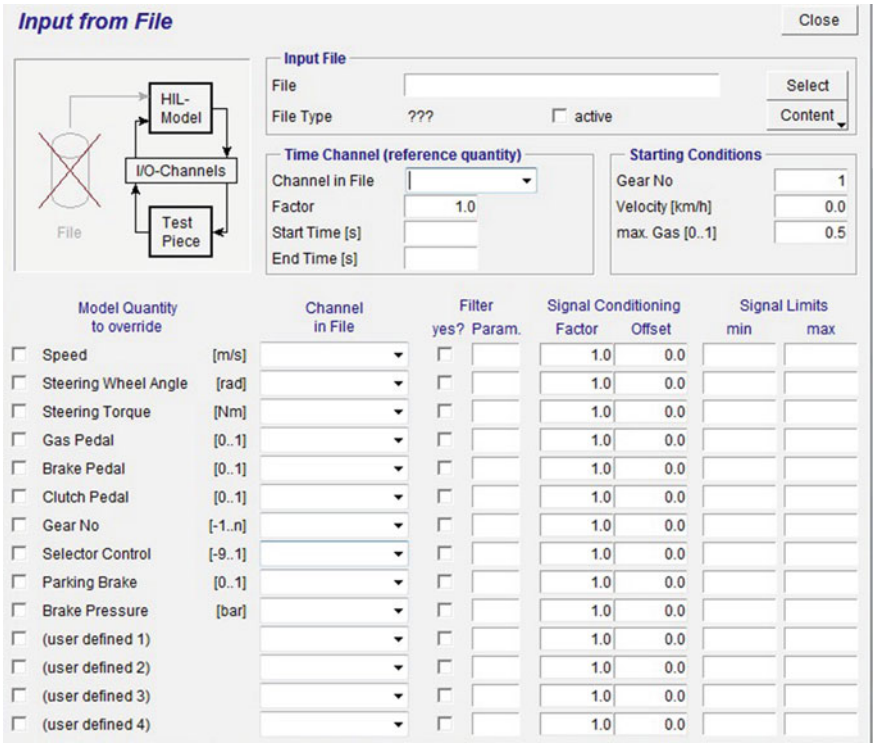


Fig. 8.35 Input From File

Several data may be read from a file: vehicle speed, steering wheel angle, steering torque, pedal position, gear number, park brake position, and the pressure in the master brake cylinder.

This functionality is referred to as *Input From File* (IFF), and its corresponding GUI can be reached via the CarMaker GUI—Parameters—Input From File.

By clicking on the GUI using the right mouse button, a context menu opens. The user can choose between *Reset*, *Load*, *Save Configuration*, *Import,* and *Edit Aliases*. The configurations can be loaded from the project, shared and central directory folder SimInput/Settings, whereas the saving of the configurations is possible only within the project directory folder SimInput/Settings.

The file containing the measurement loads is the *Input File* tab. Only one file can be chosen, thus if the measurements are split into several files, the user should gather them into a single one.

This file must be a text file without commas or other punctuation marks and should consider the following syntax: each column is referred to as a channel. Tabs are allowed to separate the columns of each channel: the first line specifies the channel names. In an optional second line, the unit and/or a factor for each channel can be specified [8].

Any input file requires a *Time Channel*. Without this channel, the IFF functionality cannot work properly. It can be selected from the available channels using a drop-down menu on the right side of the *Channel in File*. It is also possible to define channel aliases for an automatic selection of a channel. This is possible by clicking the right mouse button on the GUI and choosing *Edit Aliases*.

In the *Starting Conditions* tab the conditions for gear step, velocity, and maximum gas are used as initial values at the start of the maneuver.

In order to have a steady situation at the start of the maneuver, CarMaker starts a procedure to reach these values. The parameterized maneuver does not start and the simulation status in the CarMaker GUI remains on *Preparation* as long as the *Starting Conditions* are not reached.

Selecting and formatting the *Quantities to overwrite* are the list of the quantities that may be overwritten. In fact, it cannot be overwritten by the IFF functionality. This channel is used by functionality, the option *Speed Profile* for the definition of the longitudinal dynamics in the maneuver GUI.

The four last quantities are referred to as user defined. This means that the user can link other quantities to the IFF functionality via the C-interface of CarMaker.

IPGDriver calculates a static desired course at the beginning of the simulation. During this calculation the driver is able to optimize the path with respect to corner cutting [5]. IPGDriver is a controller for following a course and a speed controller on a given track (Fig. 8.36).

IPGDriver enables you to add the control actions of a human driver to your complete vehicle simulation. These actions include the steering, braking, throttle position, gear shifting, and clutch operation. To sum up, the driver actions are:

- Choice of driving course within the lane borders (corner cutting);
- Steering;
- Choice of the driving speed according to the course and the vehicle behavior;
- Influence on the speed over the accelerator and brake pedal, as well as over the clutch pedal and gear selection;
- Regard traffic objects and follow.

CarMaker includes two versions of IPGDriver:

- User parameterized driver: this model is part of every version of CarMaker. The user parameterized driver can perform a driver adaptation to automatically learn about the vehicle limits by performing a preset sequence of maneuvers;
- Racing driver: this model is available in the pro version of CarMaker and enables the optimization of the lap time in function of the speed and to perform a driver adaptation procedure to automatically find these limits.

The option *User parameterized Driver* allows parameterization of the driver model in the tab *Standard Parameters*.

IPGDriver is able to recognize traffic objects driving ahead. If the check box *Traffic* is activated, the driver will follow the traffic objects (Fig. 8.37).

Using the *Environment* GUI (Fig. 8.38), it is possible to define environmental conditions like the temperature, the time of day, or the wind velocity for the

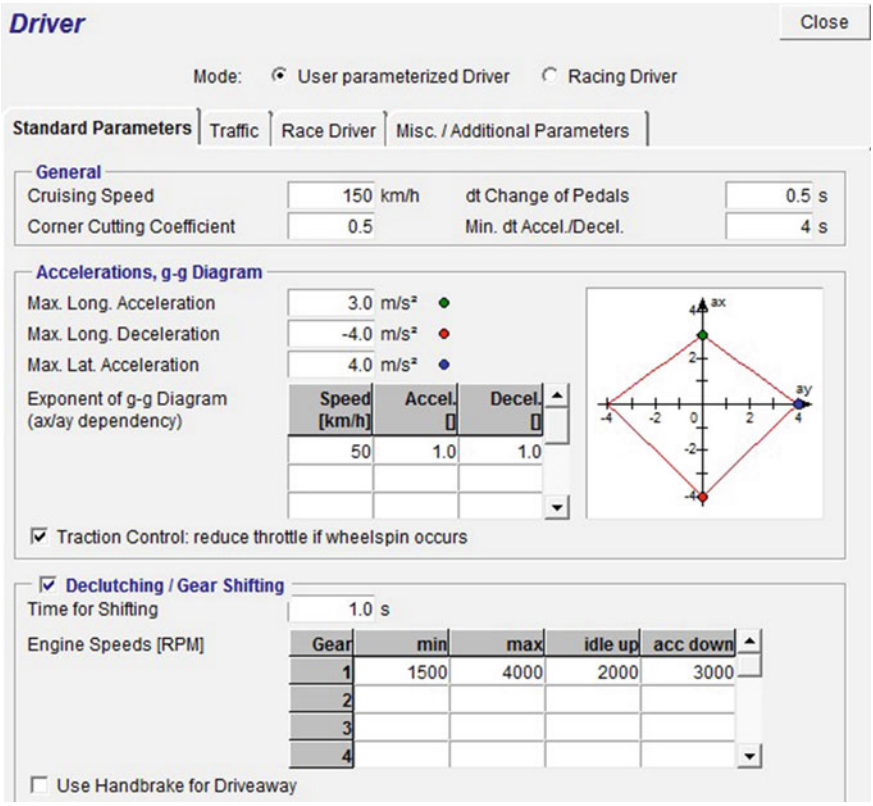


Fig. 8.36 IPGDriver—standard parameters

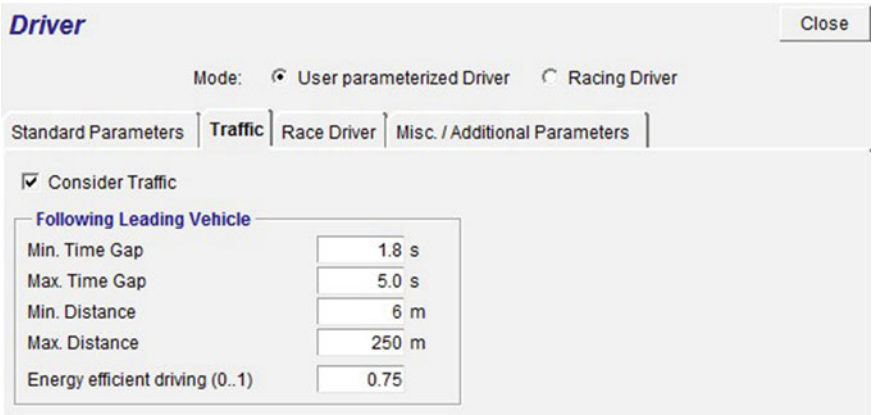


Fig. 8.37 IPGDriver—traffic

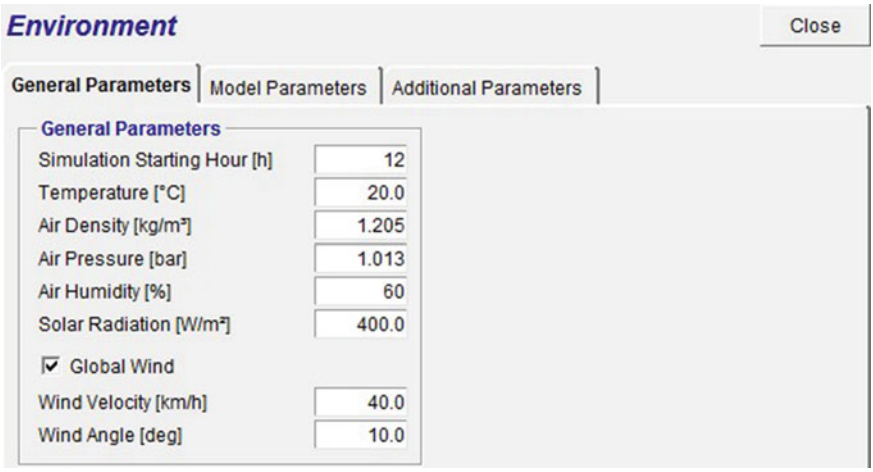


Fig. 8.38 Environment

simulation [6]. If the model takes these parameters into account, they can influence the results of the simulation.

The generic model uses a simplified approach to calculate the environmental air temperature, pressure, and density. Other environmental parameters are kept constant. It is possible to define temperature offsets depending on the time of day and/or distance. Both offsets can be defined via the look-up tables.

8.1.4 Start Simulation

To start the first simulation (Fig. 8.39) open TestRun (File—Open—Examples—Vehicle Dynamics—Training). Start the simulation by hitting the green Start button in the CarMaker GUI. Open the Instruments (File—Instruments) and open IPGMovie (File—IPGMovie).

When the user starts the simulation for the first time, the CarMaker GUI connects itself to the application. If all preparations are completed, the program is really performing the simulation of the TestRun. It normally remains in this state until the TestRun ends or is aborted because of some error condition or manual intervention of the user [9].

IPGControl is a tool that displays diagrams (Fig. 8.40). To use IPGControl online load the work model and start a simulation. A diagram is created by choosing the Quantities (Car.ax, DM.Brake, DM.Steer.Ang, etc.) and the Reference Quantity (Time).

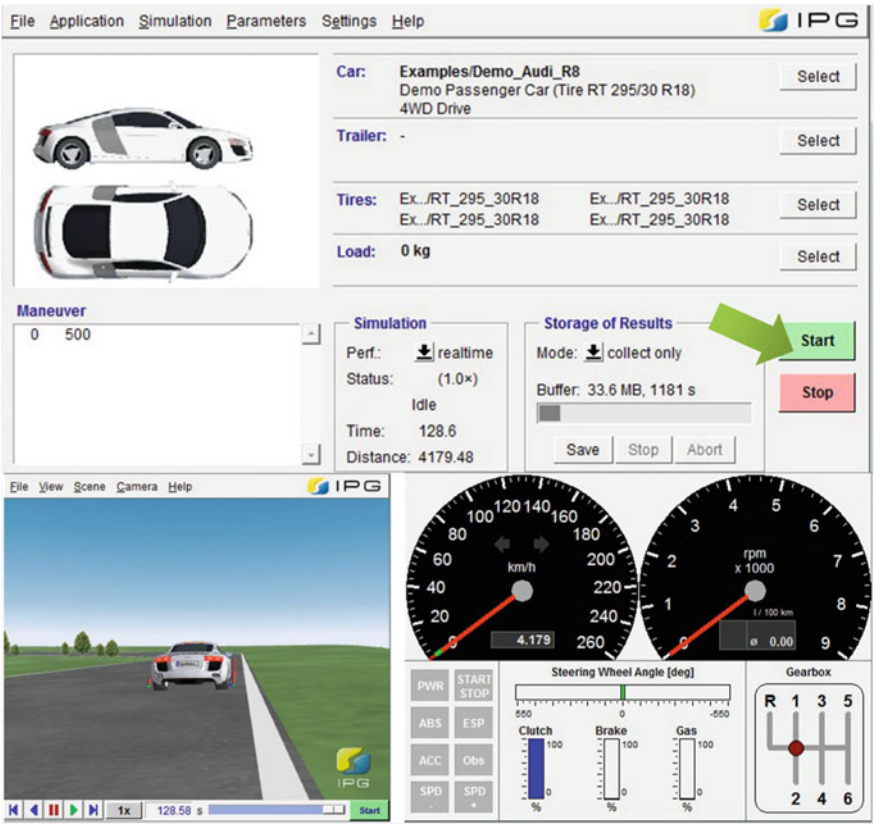


Fig. 8.39 Simulation—IPGMovie and Instruments

To use IPGControl offline, perform a simulation and select save to the store of results. In IPGControl load the File—Load File—SimOutput—NameOfPC—Date—model_name.erg. After selecting the result file to be loaded, it appears in the list of available data sets [2].

Session log window is opened automatically if errors occur. It can be opened manually over main menu from: Simulation—session log (Fig. 8.41).

Session log is found in the Simulation menu and that is a record of events for each simulation in a log file. Indeed, it is useful to keep a history of important or unusual situations and events during the simulation of a TestRun that does not disappear when the simulation is finished or the user turns off the computer. This might be of particular interest for test automation, as the user can trace any potential errors that might have during a given session.

By pressing the Analyze button the user will proceed to the system analysis. Its results will be displayed and classified according to the following criteria [2]:

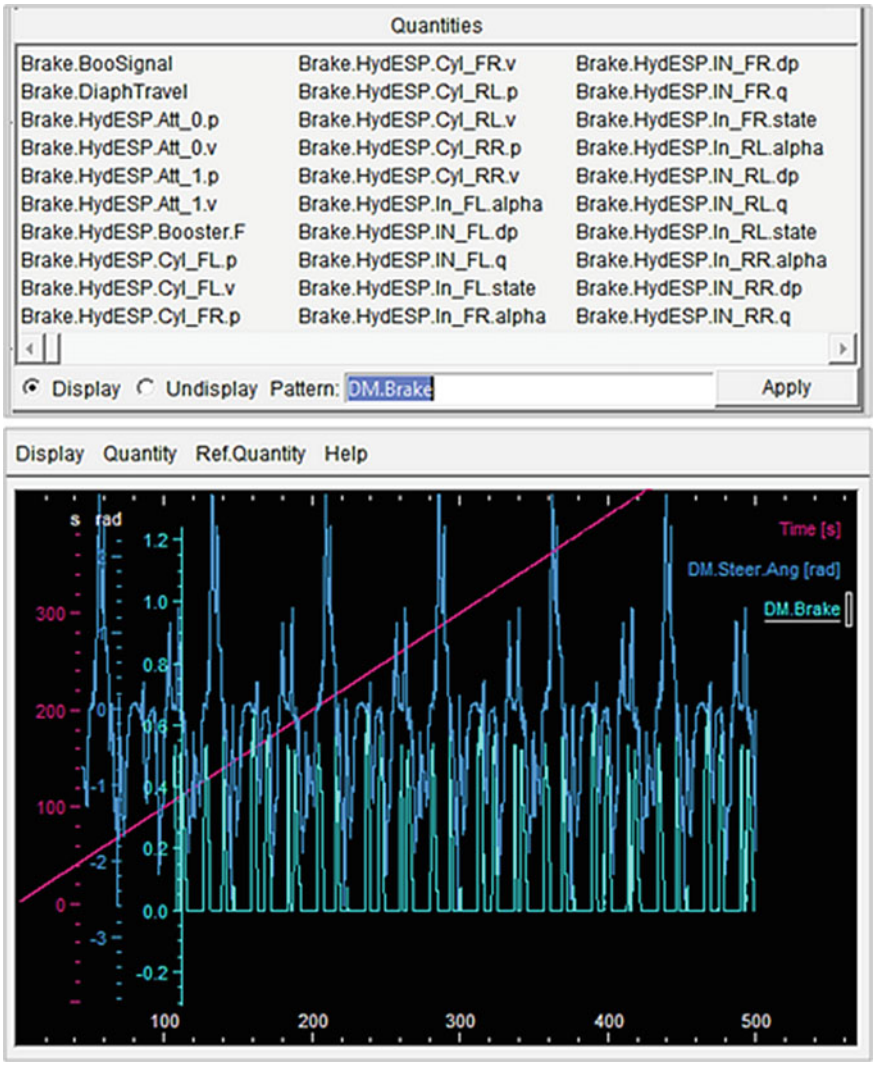


Fig. 8.40 Simulation—IPGControl

- Project: a list of all projects (defined with Settings > Result Folder) that displays the total simulation time and distance for each project.
- User: all users that have run simulations on the system are listed in this section. Total simulation time and distance for each project are shown as well.
- TestRun: TestRun files that have been loaded and played in the defined time frame appear in this section with total simulation time and distance.



Fig. 8.41 Opening session log window

8.2 CRUISE—CarMaker Co-Simulation

8.2.1 General Settings

The AVL CRUISE simulation tool is developed by the Advanced Simulation Technologies (AST) team of the AVL List GmbH. AVL CRUISE is software for vehicle's driving performance, fuel consumption, emissions, and driving quality simulation.

Although AVL CRUISE is able to simulate the whole vehicle, the focus is on the simulation of the powertrain.

AVL CRUISE reduces the analysis effort with a ready-to-use vehicle analysis platform. Vehicle modeling of any powertrain topology with scalable fidelity is done with a unique sub-system layer concept. This approach enables the reuse of models or any of its sub-systems, exactly matching the application needs in different development phases of a consistent vehicle development process [10].

AVL CRUISE allows the simulation of vehicle driving performance, fuel consumption, and emissions. This concept can be used for modeling all vehicle configurations with scalable fidelity. This approach allows the reuse of models or sub-systems in different optimization phases of a process in order to improve vehicle performances.

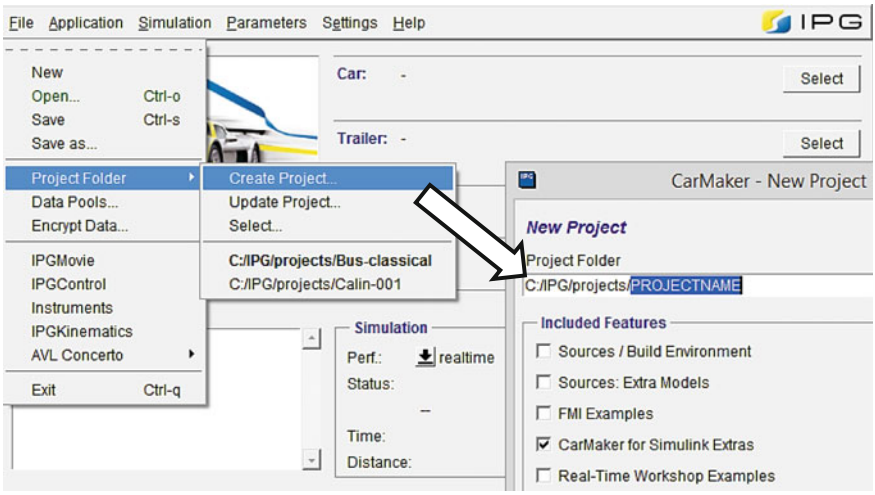


Fig. 8.42 Creating working directory

If a AVL CRUISE powertrain is chosen in the vehicle data set CarMaker starts the AVL CRUISE simulation program during the initialization phase of the TestRun simulation.

A CarMaker working directory is created over main menu File—Project Folder—Create Project (Fig. 8.42).

Selecting CarMaker working directory over main menu: File—Project Folder—Select (Fig. 8.43).

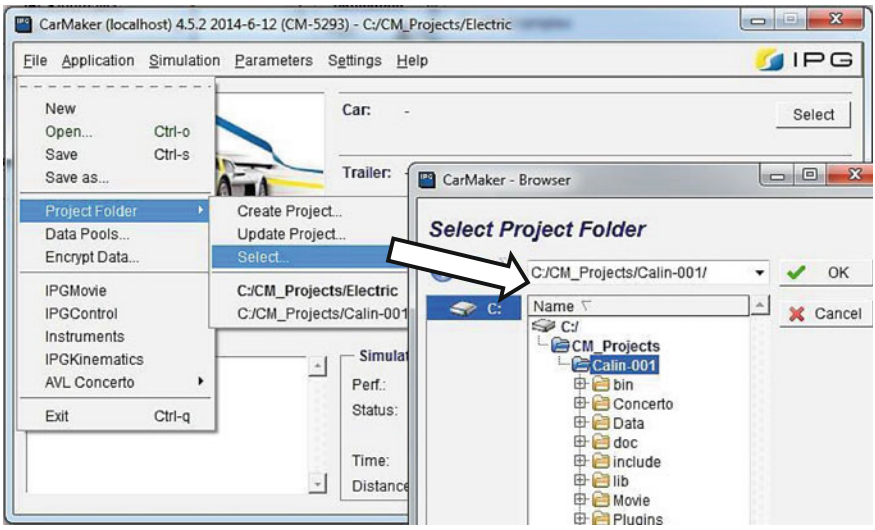


Fig. 8.43 Selecting working directory

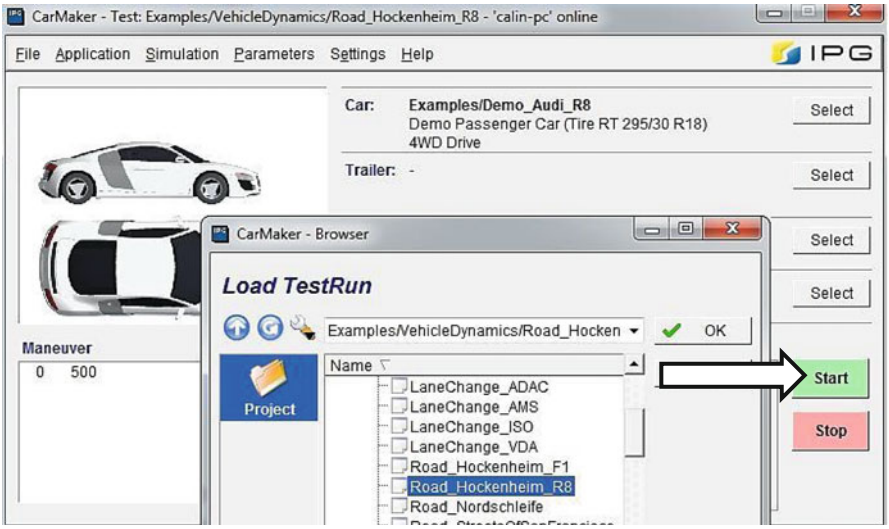


Fig. 8.44 Stand-alone simulation

After creating and selecting the working directory, CarMaker is supposed to be ready to run. To test CarMaker stand-alone simulation open one of the examples over File—Open—Examples—VehicleDynamics—Road_Hockenheim_R8 and then press Start button and the simulation should run (Fig. 8.44).

8.2.2 CRUISE—CarMaker Interfaces

Preparing a AVL CRUISE powertrain for CarMaker co-simulation requires the introduction of several new components in AVL CRUISE (CM-Car and Hub component) as well as usage of system GUI feature and SAM calculation task. On AVL CRUISE side the preparation for co-simulation are [11]:

- Building model with specific components—modules for co-simulation (CM-Car and Hub module);
- Using system/sub-system to switch between AVL CRUISE stand-alone simulation and co-simulation with CarMaker;
- Setup SAM calculation task of co-simulation;
- Some special modules needed for AVL CRUISE stand-alone simulation must be excluded in co-simulation model (Vehicle, Cockpit, etc.);

On CarMaker side the preparation for co-simulation are:

- Creating CRUISE working directory inside a directory CarMaker;

- Copying and renaming the calculation kernel file (CRUISE\bin\CRUISE_m.dll in CarMaker\lib\CRUISENT.dll) inside directory of CarMaker;
- Selecting AVL CRUISE powertrain and Project Folder for co-simulation.
- On both AVL CRUISE and CarMaker the preparations for co-simulation are:
- Harmonizing SimParameters and Memory Management.

The CM-Car component defines the interface in co-simulation between AVL CRUISE powertrain models calculated by SAM calculation task and CarMaker simulation package (Fig. 8.45) [12].

The interface component is exchanging the information between AVL CRUISE and CarMaker and there must be one CM-Car module in the vehicle model.

At every time step, AVL CRUISE data will go to the CarMaker application through Data Bus input channels *CRUISE to CarMaker*, and from there, the data comes back to AVL CRUISE through output channels *CarMaker to CRUISE* which can be connected with AVL CRUISE components [11].

This interface allows the user to easily establish a working AVL CRUISE powertrain model for CRUISE—CarMaker co-simulation. The main settings to be entered in the CM-Car interface are the following:

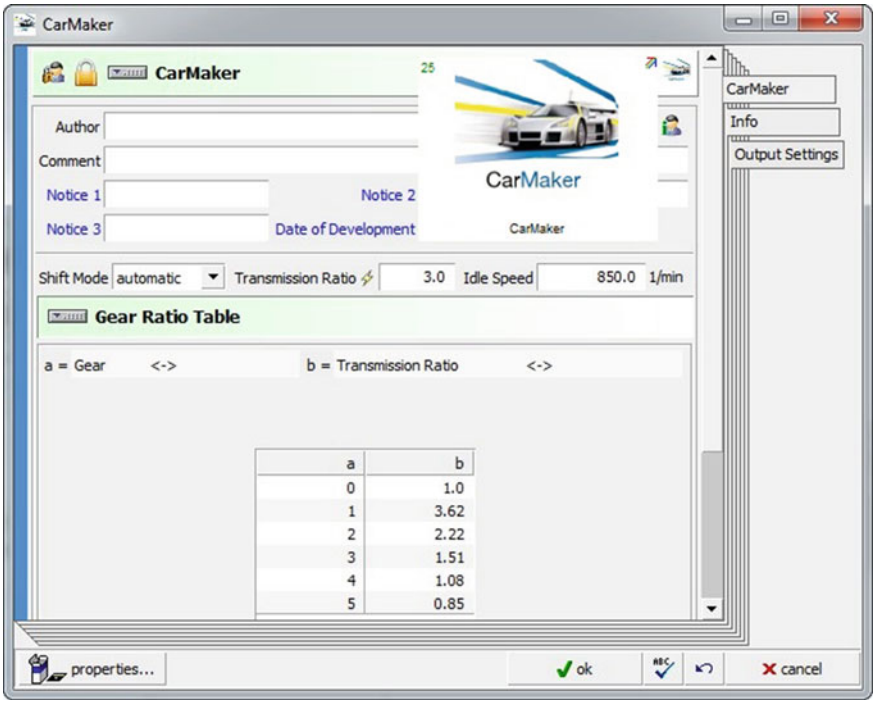


Fig. 8.45 CM-Car component in AVL CRUISE

- Manual or Automatic Shift Mode—information about using gearbox in vehicle model and it is needed by the IPGDriver;
- Transmission Ratio—the complete transmission ratio between the gearbox output speed and wheel speed and it is needed by the IPGDriver;
- Idle Speed—the value has to be consistent with the engine idle speed inside the engine module;
- Gear Ratio Table—value of the transmission ratio for complete gearbox and supposed to be consistent with transmission ratio values in gear ratio table of gearbox module;
- Body—the drive torque is supported by the car chassis;
- Wheel carrier—the drive torque is supported by the wheel carrier.

The component hub is a combination of a brake and a virtual wheel (Fig. 8.46). It is used in models with an interface to a co-simulating program which simulates the environment, the vehicle, and the wheel [11].

The component has the Data Bus inputs braking torque and (wheel) resistance torque which can be connected with an interface component like AVL CRUISE interface or CM-Car.

Inertia moment input is actually not necessary because this value is overwritten with the wheel inertia given in the vehicle data set of CarMaker.

To avoid problems with slightly rotating wheels during standstill it is recommended to uncheck the dynamic mode. dynamic mode is deactivated by default. Deactivation may be done in modeling a sticking brake in kinematic mode. When

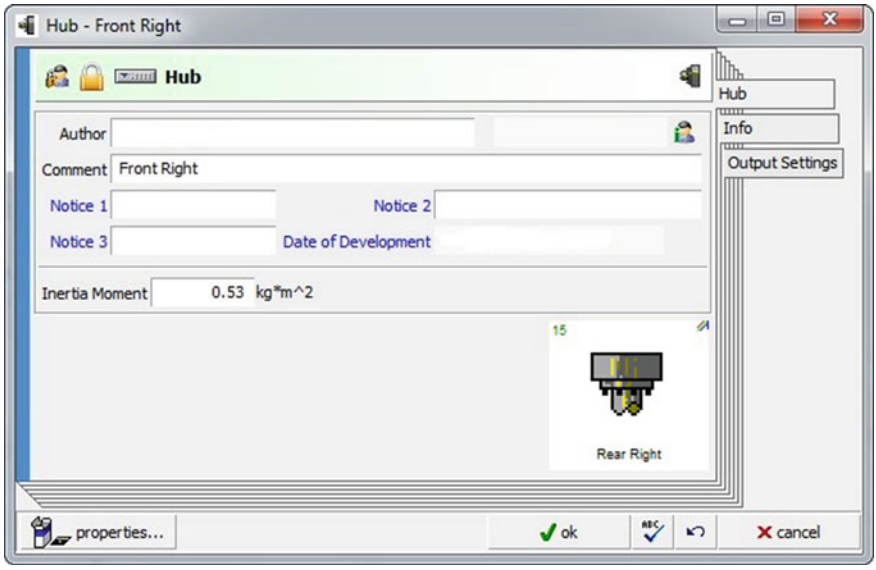


Fig. 8.46 Hub component in AVL CRUISE

set to dynamic, the brake calculation always stays dynamic and never switches to a kinematic connection.

The most important aspect is that there are exactly the same numbers of Hub modules as wheels in the model and they are properly connected or positioned like in the AVL CRUISE stand-alone model. The hub location change is done in the properties dialog by choosing a proper location from the pull-down menu.

SAM (System Analysis Mode) folder with system analysis task is added in the calculation task by default (Fig. 8.47).

The system analysis simulation is used to analyze the parts of the driveline or components in sub-system. It is switched on/off with a check box on the Calculation Center application form.

There is no need to define standard vehicle specific tasks such as Cycle Run, Full Load Acceleration, etc. Components Cockpit, Vehicle and task components Driver, Course and Profile are also not required.

SAM Task will be used in AVL CRUISE powertrain model for calculation of powertrain quantities which are required and transferred to CarMaker application [11].

The model with the interface for co-simulation developed in AVL CRUISE will be saved in the working folder CarMaker/CRUISE, where it will be loaded and launched as project work in the application CarMaker [11].

Choose the powertrain folder in the vehicle data set from CarMaker. In the pull-down menu choose AVL_CRUISE (Fig. 8.48).

To include the AVL CRUISE powertrain in the CarMaker simulation environment, click on the Browse button to select the desired AVL CRUISE powertrain. Select Open and AVL CRUISE powertrain will be integrated into the CarMaker simulation environment as shown in the following figure.

In order to really include AVL CRUISE powertrain in CarMaker simulation environment, press folder button to select desired AVL CRUISE powertrain. In the *Project* input field there must be a path to the AVL CRUISE PRJ file. Select Open and AVL CRUISE powertrain will be integrated into CarMaker Simulation Environment (Fig. 8.49).

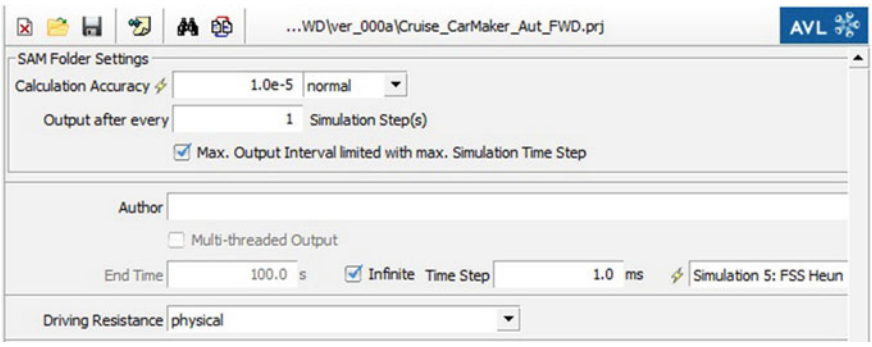


Fig. 8.47 SAM (System Analysis Mode) folder

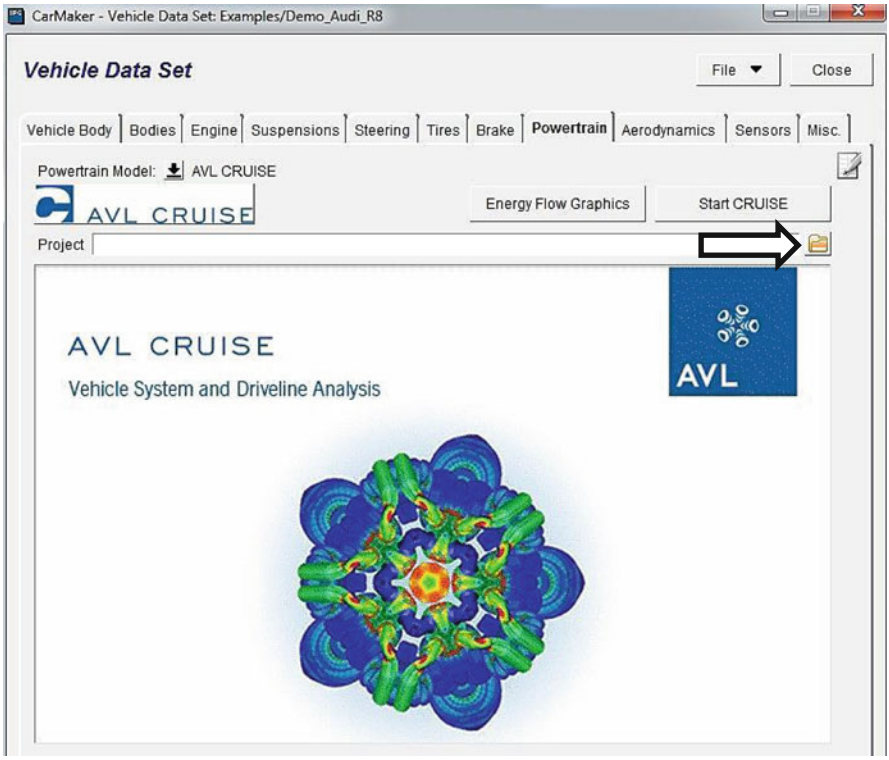


Fig. 8.48 CRUISE—CarMaker interface

For the purposes of this manual a AVL CRUISE powertrain model will be constructed from scratches, using only one standard AVL CRUISE model. Therefore, select that model using the Start AVL CRUISE command.

8.2.3 Model for Co-Simulation

In order to make the final step toward including AVL CRUISE powertrain in CarMaker environment is, enough to select already prepared AVL CRUISE powertrain model through CarMaker File Explorer and press Open.

AVL CRUISE will open and when selecting Vehicle Model, the user can view and extract it from the AVL CRUISE GUI screen (Fig. 8.50).

This AVL CRUISE model consists of one system and one sub-system, i.e., all model components are contained in one sub-system of the model. In order to prepare AVL CRUISE powertrain model for CarMaker co-simulation the user has to create two systems, each with three sub-system.

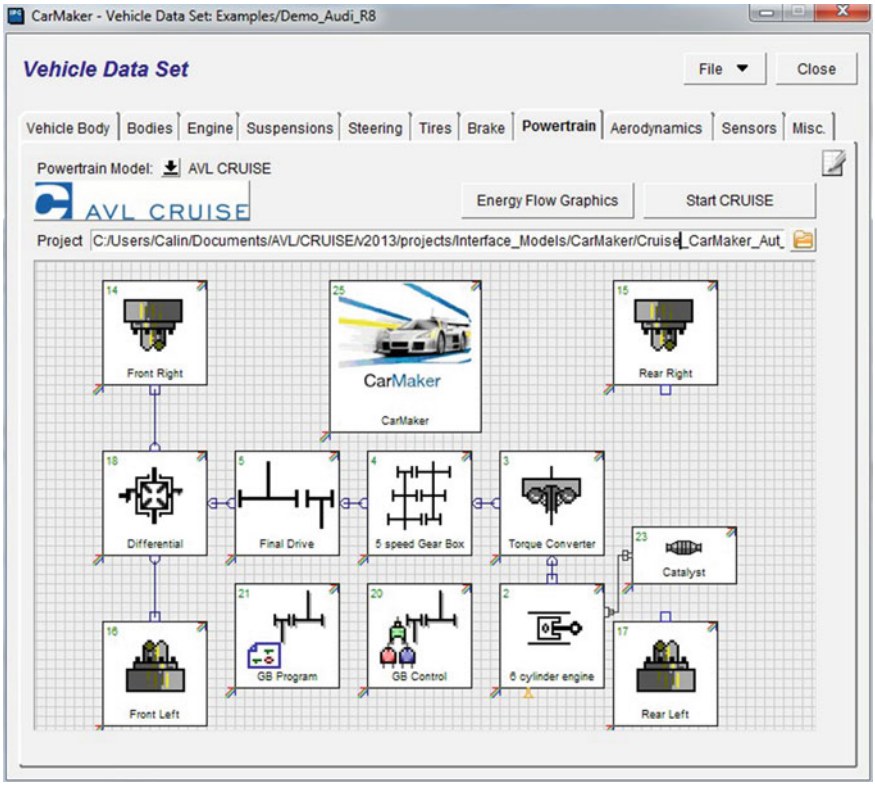


Fig. 8.49 AVL CRUISE powertrain integrated into CarMaker

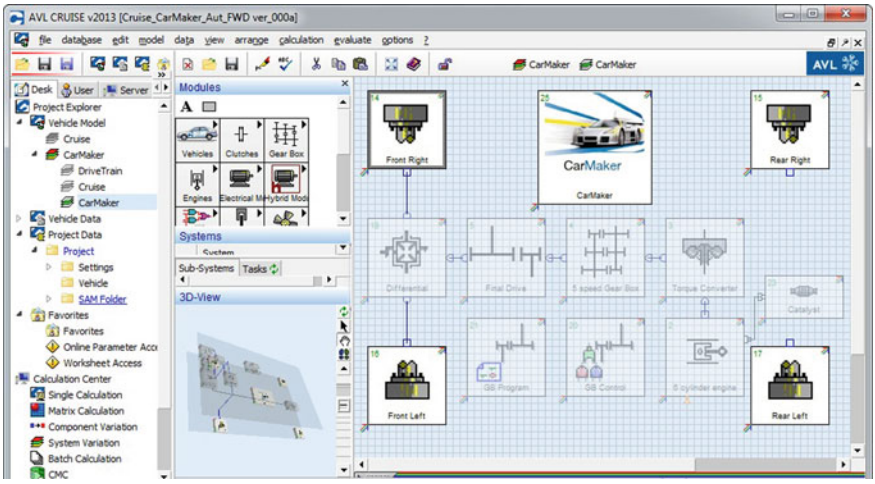


Fig. 8.50 Vehicle Model in AVL CRUISE

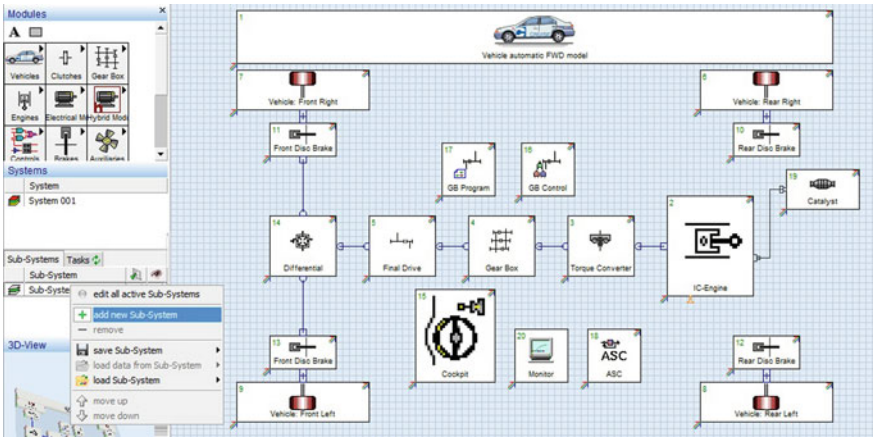


Fig. 8.51 Adding a new sub-system

First step is to add two sub-system in the current system. Right click on sub-system 001 in sub-system window part and select add new sub-system options as shown in Fig. 8.51.

Repeat this procedure to create another sub-system in system 001. The result of this procedure should be one system with three sub-systems (sub-system 001, sub-system 002, and sub-system 003) [11].

In order to distinguish all further actions in system and sub-system structure rename the current system into AVL CRUISE, sub-system 001 into Vehicle, sub-system 002 into Powertrain, and sub-system 003 into CarMaker. After that, select all components that are not part of the powertrain and right click somewhere in the Vehicle Model area and then select sub-system—Vehicle. All selected components will be added to the Vehicle sub-system of the AVL CRUISE system [11].

Additionally, the powertrain components of Aut FWD model must be added to the Powertrain sub-system of AVL CRUISE system. To do so, select all remaining components in Vehicle Model window again, right click somewhere in Vehicle Model area and then select sub-system—Powertrain (Fig. 8.52).

The selected components for the Vehicle sub-system are: Vehicle, Wheels, Brakes, Catalyst, Cockpit, Monitor, and ASC.

Hence that CarMaker sub-system of AVL CRUISE system contains no components so far. Therefore, we added already mentioned components CM-Car and hub to the CarMaker sub-system (Fig. 8.53). CM-Car and hub components can be found in Modules—Special Modules section. Select CarMaker sub-system in AVL CRUISE system and use drag&drop technique to add one CM-Car component and four hub components to that sub-system. Since the hub component in fact represents brake and virtual wheel, mechanical connection must be made so that front axle hub components are connected to the differential.

Complete CarMaker Sub-System can be loaded with corresponding modules. With a right mouse button click on sub-system area and from sub-systems popup

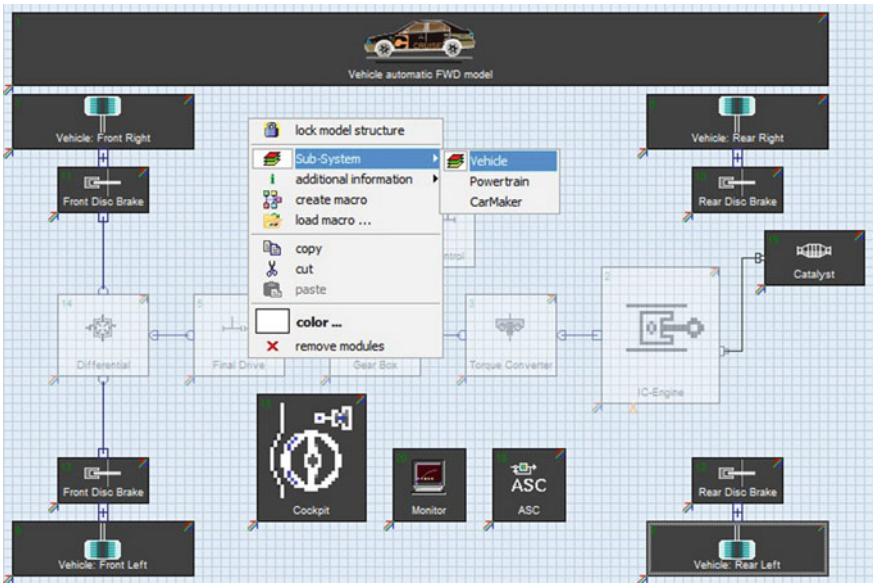


Fig. 8.52 Adding selected components to the Vehicle sub-system

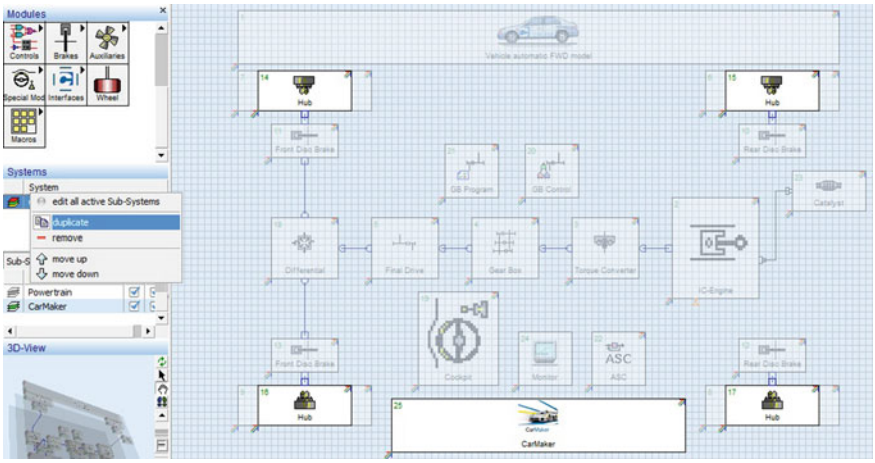


Fig. 8.53 CarMaker sub-system

menu load CM-Car.sub from directory data\sub_system. After, rename and arrange CarMaker sub-system, select each component and adjust it with move and stretch to gain position and shape/look of the current model.

Next step is to make a distinction between AVL CRUISE simulation model and CarMaker specific AVL CRUISE powertrain model. Therefore, we will first create

a copy of the built system. Right click on AVL CRUISE system, select duplicate and rename the created system into something more intuitive CarMaker PT.

Deselect activation and visibility of AVL CRUISE sub-system, while it is not part of the CarMaker PT system and establish missing mechanical connection from the differential to each of the front hubs.

There are now two systems (AVL CRUISE and CarMaker PT), each with three sub-systems (Vehicle, Powertrain, and CarMaker). Next step is to group some of the sub-systems into each system: AVL CRUISE System includes Vehicle and Powertrain (Fig. 8.54), CarMaker PT system and includes Powertrain and CarMaker (Fig. 8.55).

The connections in the data bus for CarMaker sub-system are described in Table 8.1 and in Fig. 8.56.

The connections in the data bus for the drivetrain sub-system are described in Table 8.2.

After all necessary connections have been established go to Calculation Center of AVL CRUISE and activate SAM Task and adjust parameters with the following values:

- End Time: check *Infinite* option;
- Time Step: 0.001 (s);
- Simulation 5: FSS Heun.

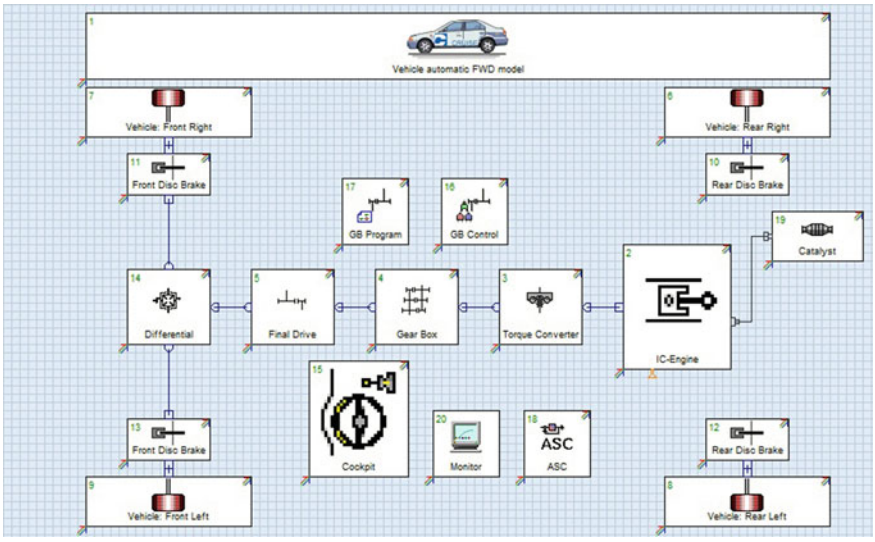


Fig. 8.54 AVL CRUISE system

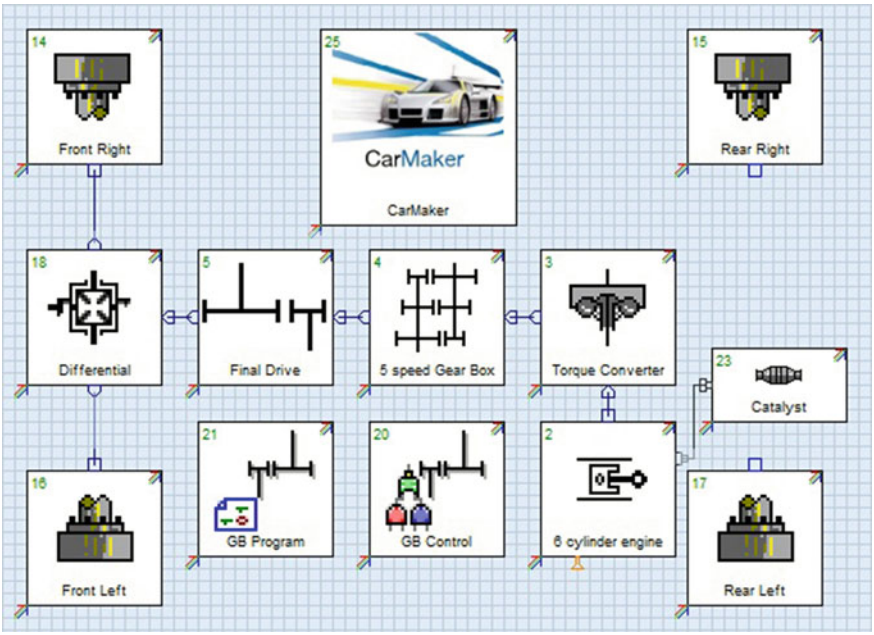


Fig. 8.55 CarMaker PT system

Table 8.1 Data Bus connection for CarMaker sub-system

Component Requires	Input Information	Component Delivering	Output Information
CarMaker	Drive Torque FL	Differential	Output Torque 1
	Drive Torque FR	Differential	Output Torque 2
	Engine On/Off	Engine	Operation Control
	Engine Speed	Engine	Engine Speed
	Engine Torque	Engine	Engine Torque
Hub Front Right	Braking Torque	CarMaker	Braking Torque FR
	Resistance Torque	CarMaker	Resistance Torque FR
Hub Rear Right	Braking Torque	CarMaker	Braking Torque RR
	Resistance Torque	CarMaker	Resistance Torque RR
Hub Front Left	Braking Torque	CarMaker	Braking Torque FL
	Resistance Torque	CarMaker	Resistance Torque FL
Hub rear left	Braking Torque	CarMaker	Braking Torque RL
	Resistance torque	CarMaker	Resistance Torque RL

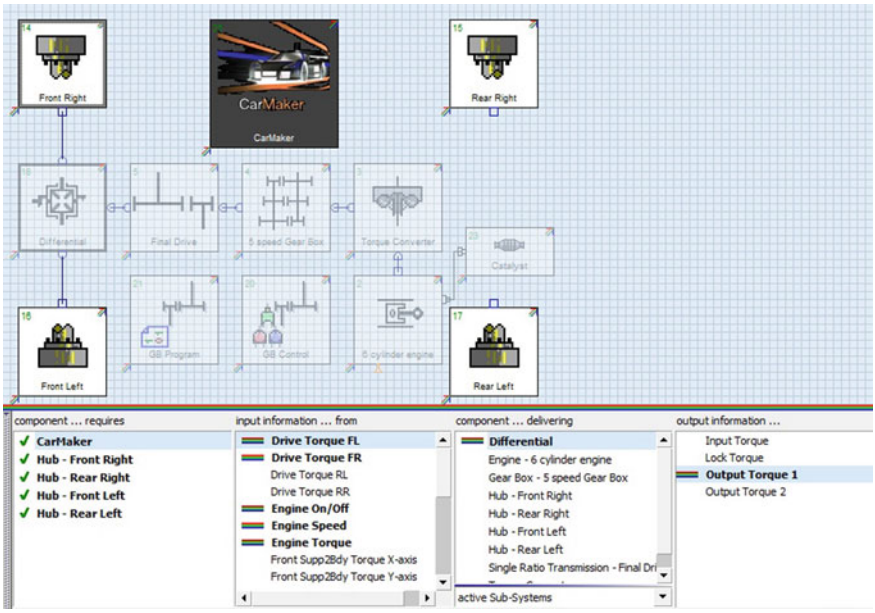


Fig. 8.56 Data Bus connection for CarMaker

Table 8.2 Data Bus connection for drivetrain sub-system

Component Requires	Input Information	Component Delivering	Output Information
Engine	Load Signal	CarMaker	Load Signal
	Start Switch	CarMaker	Engine Start Switch
Gearbox	**Desired Gear**	Gearbox Control	Desired Gear
Gearbox Control	**Current Gear**	Gearbox	Current Gear
	Desired Gear Cockpit	CarMaker	Desired Gear
	Desired Gearbox Program	Gearbox Program	Desired Gear
	Operation Control	Engine	Operation Control
	Reference Speed	Torque Converter	Turbine Speed
	Velocity	CarMaker	Vehicle Velocity
Gearbox Program	**Current Gear**	Gearbox	Current Gear
	Load Signal	CarMaker	Load Signal
	Speed	Gearbox	Output Speed

8.3 Running the Simulation for Electric Model

To run the simulation, first the model must be connected with AVL CRUISE, (connection with the desired model must be checked), and then the road must be loaded, with the desired maneuvers.

To check the connection with AVL CRUISE, the model must be opened like shown in Fig. 8.57.

After pressing the start button, like shown in Fig. 8.39, the simulation starts. In the IPGControl data window, the user can monitor any parameters by selecting them from the quantities tab.

For the electric model the four main monitored properties are: the Current [A], the Voltage [V], Energy [kJ], and Energy Stored [kJ]. They are selected from Quantities—AVL.CRUISE.efg like shown in Fig. 8.58 and monitored in real time, as seen in Fig. 8.59.

If the user is interested in the powertrain, the parameters that can be monitored are shown in Fig. 8.60 or if the interest in the Driver, the parameters are shown in Fig. 8.61.

In order to see the whole variation of the parameters, total fit must be selected from the display tab.

After the simulation stops, and after pressing total fit, the recorded variations can be exported either as a. *csv* file and post-processed further like in Figs. 8.62, 8.63 and 8.64, or they can be saved as they were recorded and printed (Fig. 8.65).

By exporting the Current [A], the Voltage [V], Energy [kJ] and Energy Stored [kJ], the user can analyze the state of the battery, the recovered energy either versus elapsed time, or by the track. Basically, the user can conclude which is the optimal track for recovered energy or underline the optimal range.

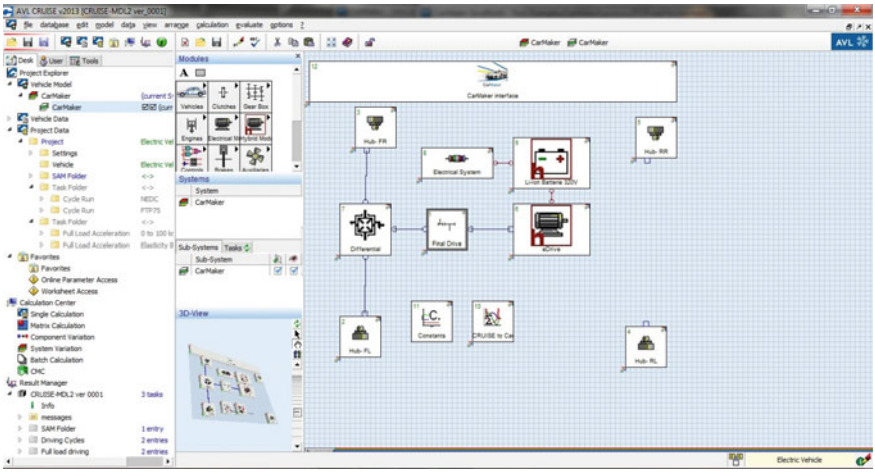


Fig. 8.57 Connection to AVL CRUISE check (electric model)

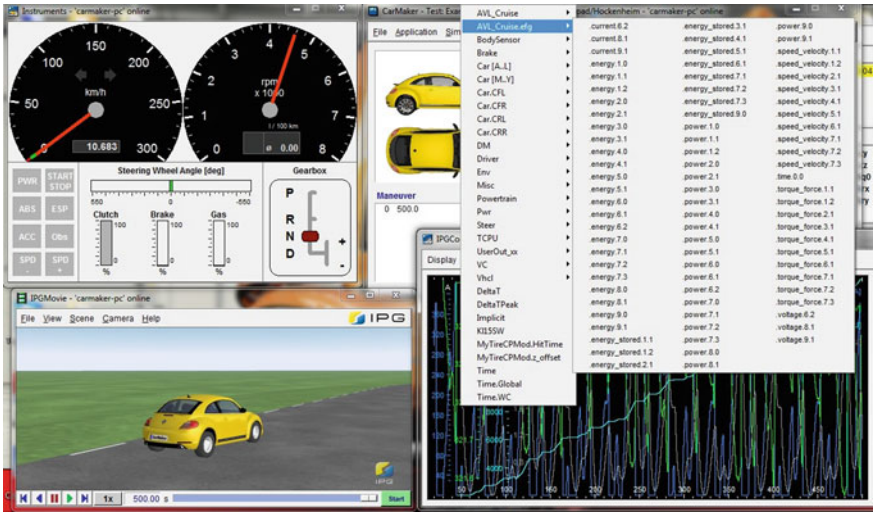


Fig. 8.58 Selecting the desired properties to monitor

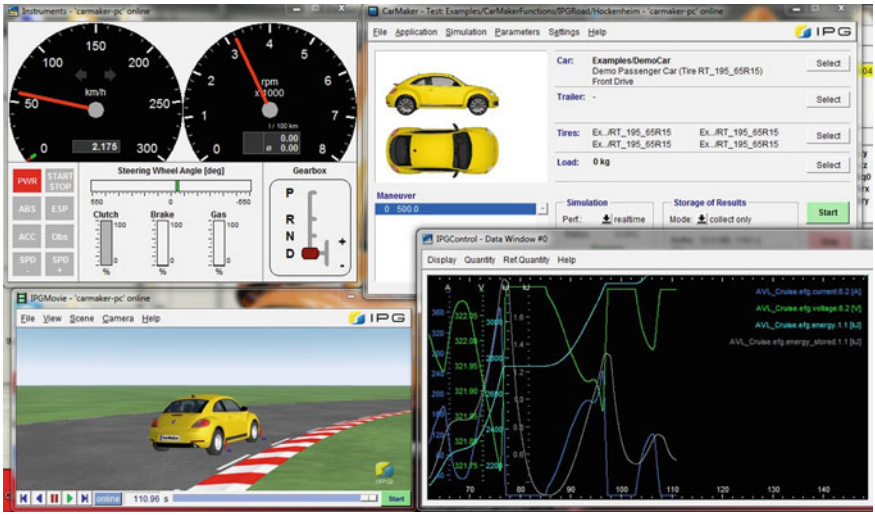


Fig. 8.59 Monitoring the electric model in the IPGControl data window

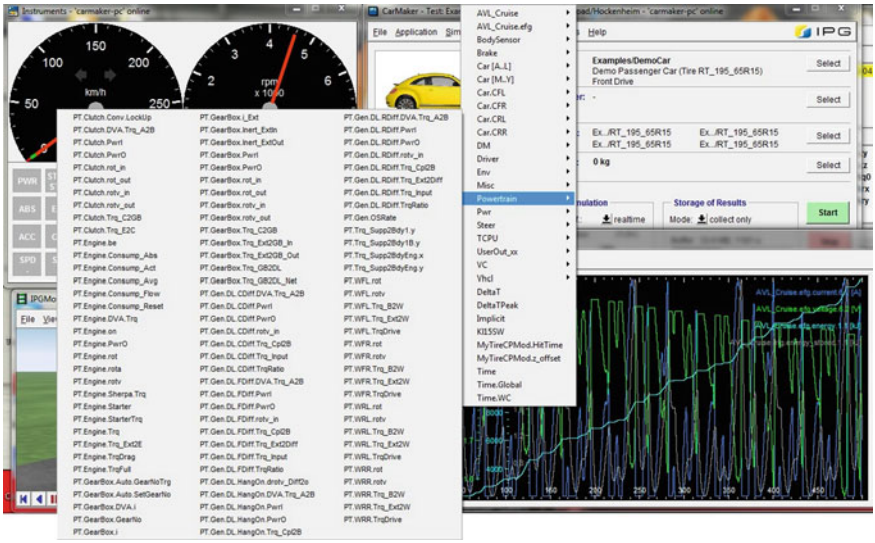


Fig. 8.60 Monitoring the Powertrain properties

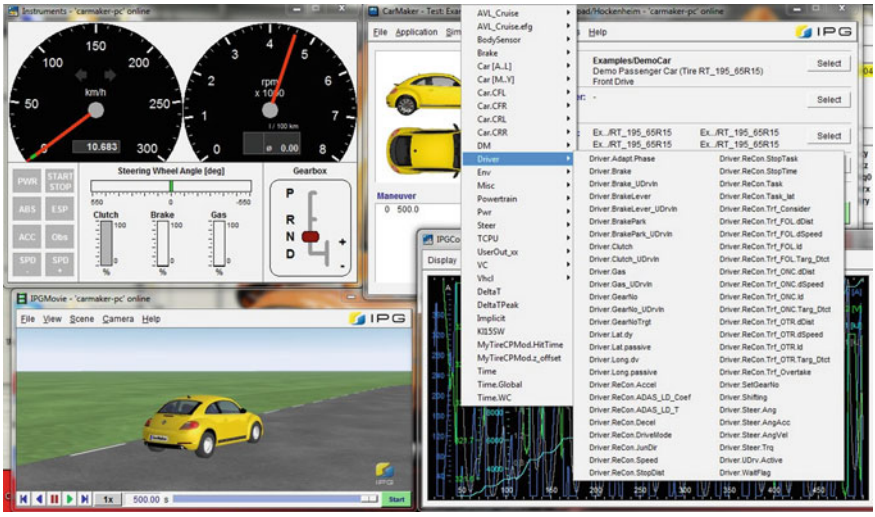


Fig. 8.61 Monitoring the Driver properties

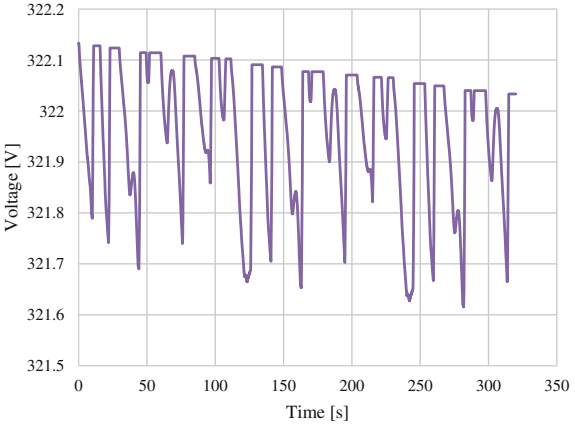


Fig. 8.62 Export of the recorded data: Voltage

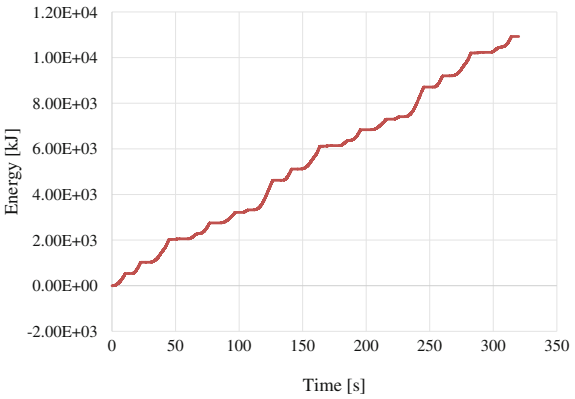


Fig. 8.63 Export of the recorded data: Energy

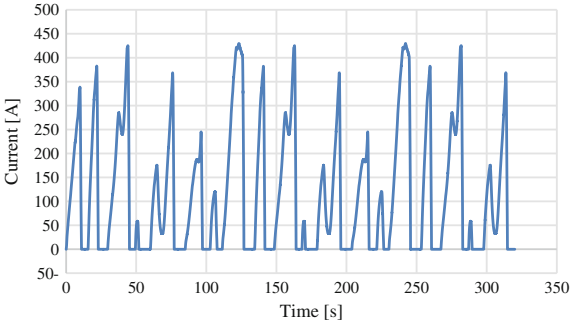


Fig. 8.64 Export of the recorded data: Current

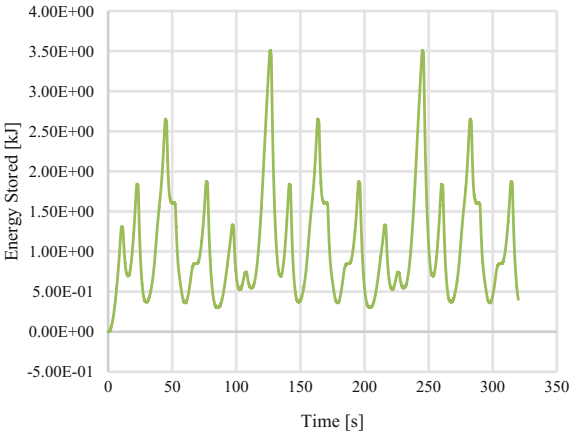


Fig. 8.65 Export of the recorded data: Energy Stored

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