

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

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
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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
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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
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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
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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).

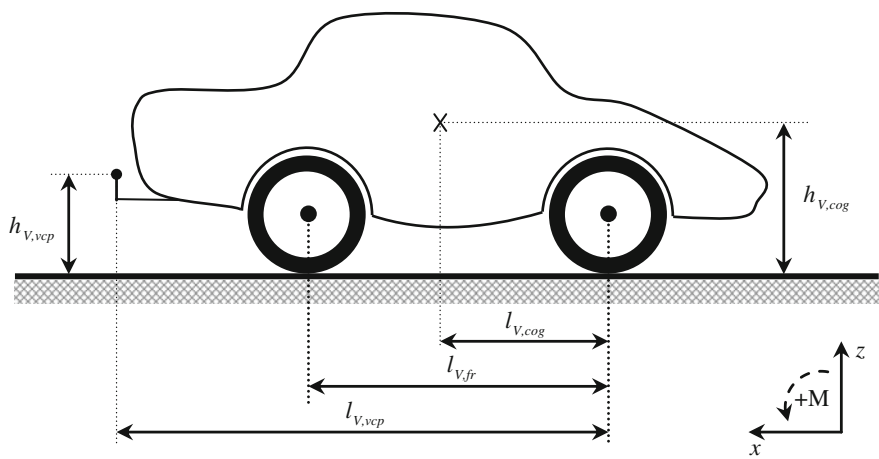


Fig. 2.1 Vehicle nominal dimensions [2]

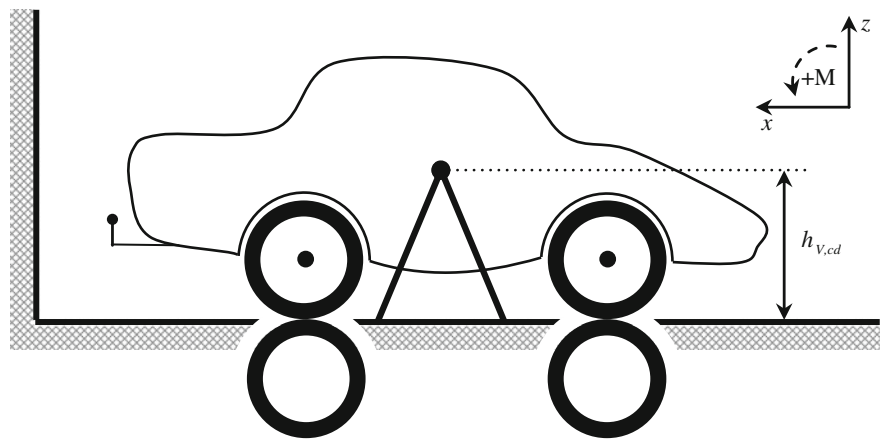


Fig. 2.2 Support point at bench test [4]

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

$m_{V,zul}$	Gross Weight	kg
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The Gross weight is the maximum admissible weight of the vehicle.

Air Coefficient

A_v	Frontal Area	m ²
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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	–
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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

$l_{front,rear}$	Track Width Front/Rear	mm
$C_{\alpha-front,rear}$	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	–
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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
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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
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In addition, the following data of the reference vehicle have to be defined:

$m_{V,ref}$	Weight	kg
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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	–
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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

$$m_{V,act} = m_V(z_{V,load}) \quad (2.1.1)$$

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

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

(b) **If an additional mass describes the load**

The instantaneous vehicle mass is evaluated as followed [2]

$$m_{V,act} = m_V(0) = m_{V,zul} \quad (2.1.3)$$

2.1.5.2 Number of Wheels

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

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]**

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

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

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]:**

$$h_{V,cog,act} = h_{V,cd} \quad (2.1.6)$$

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]

$$F_A = m_{A,virt} \cdot [a_V + g \cdot \sin(\alpha_U)] + F_{A,virt} \cdot \cos(\alpha_U) \quad (2.1.7)$$

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]:

$$\sum M_{r,ax} = 0 \quad (2.1.8)$$

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

$$F_{w,x,f,ax} = m_{V,act} \left[\left(1 - \frac{l_{V,cog,act}}{l_{V,fr}} \right) \cdot g \cdot \cos \alpha_U - \frac{h_{V,cog,act}}{l_{V,fr}} \cdot (a_V + g \cdot \sin \alpha_u) \right] - F_{V,lift,f} \quad (2.1.9)$$

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]:

$$F_{W,x,f,r} = \frac{F_{W,x,f,ax}}{2 \cdot N_{W,f,r}} \quad (2.1.10)$$

Left front wheel load [2]:

$$F_{W,x,f,l} = \frac{F_{W,x,f,ax}}{2 \cdot N_{W,f,l}} \quad (2.1.11)$$

Rear Axis

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

$$\sum M_{f,ax} = 0 \quad (2.1.12)$$

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

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

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]:

$$F_{W,x,r,r} = \frac{F_{W,x,r,ax}}{N_{W,r,r}} \quad (2.1.14)$$

Left rear wheel load [2]:

$$F_{W,x,r,l} = \frac{F_{W,x,r,ax}}{N_{W,r,l}} \quad (2.1.15)$$

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]

$$v_{U,V,rel} = v_V + v_{U,air} \quad (2.1.16)$$

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

Inclination Resistance [2]

$$\alpha_U = \alpha_{U,up} + \alpha_{U,dn} \quad (2.1.18)$$

$$F_{V,incl} = m_{V,act} \cdot g \cdot \sin \alpha_U \quad (2.1.19)$$

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]

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

(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]:

$$F_{V,\text{res}} = \frac{m_{\text{act}}}{m_{\text{ref}}} \cdot c_A + \frac{m_{\text{act}}}{m_{\text{ref}}} \cdot c_B \cdot v_V + \frac{c_W \cdot A}{c_{W,\text{ref}} \cdot A_{\text{ref}}} \cdot c_C \cdot v_V^2 \quad (2.1.21)$$

(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]:

$$F(v) = A + B \cdot v_V + \bar{F}(v_V) \quad (2.1.22)$$

$$\text{for } v_V = 0 \rightarrow A = F(v_V = 0) \quad (2.1.23)$$

$$B = F'(v_V = 0) \quad (2.1.24)$$

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

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

$$\bar{F}(v_V) = F(v_V) - A - B \cdot v_V \quad (2.1.25)$$

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

$$F_{V,\text{res}} = \frac{m_{\text{act}}}{m_{\text{ref}}} \cdot (A + B \cdot v_V) + \bar{F}(v_V) \quad (2.1.26)$$

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

(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]:

$$F_{V,\text{res}} = c_A + c_B \cdot v_V + c_C \cdot v_V^2 \quad (2.1.28)$$

(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].

$$F(v) = A + B \cdot v_V + \bar{F}(v_V) \quad (2.1.29)$$

$$\text{for } v_V = 0 \rightarrow A = F(v_V = 0) \quad (2.1.30)$$

$$B = F'(v_V = 0) \quad (2.1.31)$$

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

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

$$\bar{F}(v_V) = F(v_V) - A - B \cdot v_V \quad (2.1.32)$$

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

$$F_{V,\text{res}} = (A + B \cdot v_V) + \bar{F}(v_V) \quad (2.1.33)$$

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

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]:

$$F_{\text{lateral}} = F_{s,\rho} + F_{s,\text{wind}} + F_{s,\beta} \quad (2.1.35)$$

The single parts of the lateral forces can be calculated by the following formulas:

Front (rear) axle force by lateral acceleration [2]:

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

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

$$F_{s,\text{Wind}} = c_s \cdot \rho \cdot \left(\frac{v_{\text{Wind}}^2}{2} \right) \cdot A_s \cdot \sin(\alpha_{\text{Compass}} + \beta_{\text{slip}}) \quad (2.1.37)$$

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].

$$F_{s,\beta} = c_s \cdot \rho \cdot \left(\frac{v_{\text{Vehicle}}^2}{2} \right) \cdot A_s \cdot \sin(\beta_{\text{slip}}) \quad (2.1.38)$$

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].

$$d_{\text{lateral}} = l \cdot \frac{c_{\text{MZ}}}{c_s} \quad (2.1.39)$$

Front axle lateral force by crosswind [2]:

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

Rear axle lateral force by crosswind [2]:

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

- (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]:

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

Downforce wheel right (left) front [2]:

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

Downforce wheel right (left) rear [2]:

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

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

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

(4) Ackermann angle [2]:

$$\alpha_{ackermann} = \frac{b_{Wheelbase}}{\rho} \quad (2.1.46)$$

(5) Steering angle [2]:

$$\delta = \frac{\alpha_{ackermann}}{1 + \frac{F_{radial,f}}{c_\alpha}} + \alpha_f - \alpha_r \quad (2.1.47)$$

(6) Slip angle [2]:

$$\beta = \frac{b_{wheelbase} \cdot l_{GC}}{\delta} - \alpha_r \quad (2.1.48)$$

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.

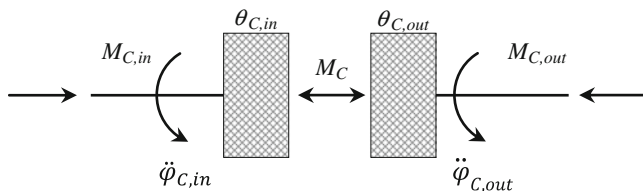


Fig. 2.3 Friction clutch model [2]

$M_{C,max}(\dot{\varphi}_{c,rel})$	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

$\dot{\phi}_{C,rel}$	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]:

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

Actual friction coefficient

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

$$\dot{\phi}_{C,rel} = \dot{\phi}_{C,in} - \dot{\phi}_{C,out} \quad (2.2.2)$$

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]:

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

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]:

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

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

$$M_C = |M_{C,in} - M_{C,out}| \quad (2.2.5)$$

Detection of sliding and adhesion

The clutch will slide as long these conditions are fulfilled:

$$[|M_{C,in} - M_{C,out}| \geq |M_C|] \vee [\dot{\phi}_{C,rel} > 0] \vee [S_{C,art} > 0.8] \quad (2.2.6)$$

The clutch will adhere for the following condition

$$[|M_{C,in} - M_{C,out}| < |M_C|] \wedge [\dot{\phi}_{C,rel} < 0.01] \wedge [S_{C,act} < 0.8] \quad (2.2.7)$$

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

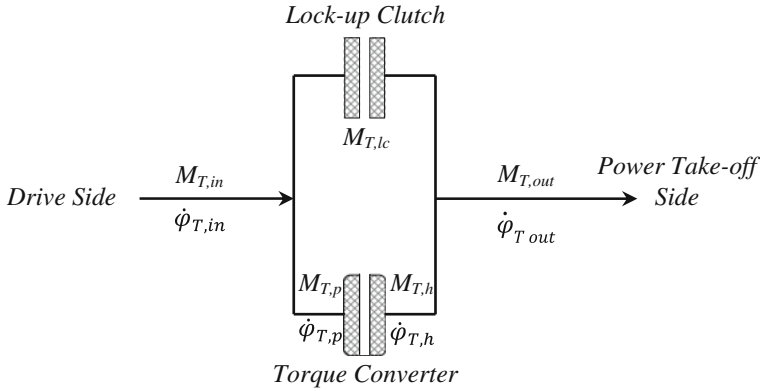


Fig. 2.4 Torque Converter with lock-up clutch model [2]

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.

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

$M_{T,lock-up,max}$	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	–
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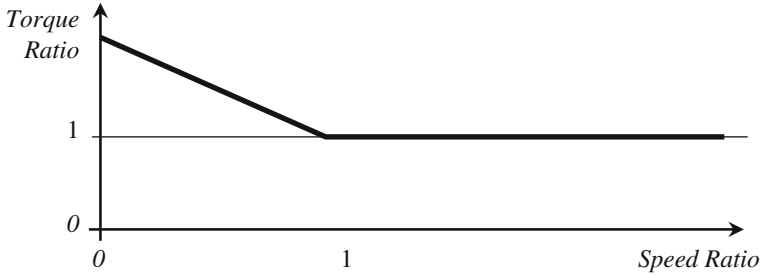


Fig. 2.5 Torque Ratio as function of the speed ratio [2]

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]:

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

$M_{T,Pump,act}$	Transferable Torque at the actual pump speed
$\dot{\phi}_{T,Pump}$	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]:

$$Cf_T = \frac{M_{T,Pump,act} \cdot 10^6}{\dot{\phi}_{T,Pump}^2} \quad (2.3.2)$$

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]:

$$K_T = \frac{\dot{\phi}_{T,Pump}}{\sqrt{M_{T,Pump,act}}} \quad (2.3.3)$$

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

$\dot{\phi}_{T,in}$	Angular velocity on the drive side	rad/s
$\ddot{\phi}_{T,in}$	Angular acceleration on the drive side	rad/s ²
$\dot{\phi}_{T,out}$	Angular velocity on the power take-off side	rad/s
$\ddot{\phi}_{T,out}$	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
$\dot{\phi}_{T,pump}$	Pump Speed	rad/s
$M_{T,pump,act}$	Pump Torque	Nm
$\dot{\phi}_{T,turb}$	Turbine Speed	rad/s
$M_{T,turb,act}$	Turbine Torque	Nm
$\dot{\phi}_{T,Mp2000}$	Mp2000 (Pump torque at pump speed 2000)	Nm
$\ddot{\phi}_{T,in}$	Pump Acceleration	rad/s ²
$\ddot{\phi}_{T,out}$	Turbine Acceleration	rad/s ²
$v_{T,act}$	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

$\dot{\phi}_{T,rel}$	Difference of angular velocities between in and off side	rad/s
$K_{T,scale}$	Scale factor	–
$v_{T,act}$	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 $\dot{\phi}_{T,in} = 0$ [2]:

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

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

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

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

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

$$v_{T,act} = 1 \quad (2.3.6)$$

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

$$v_{T,act} = \frac{\dot{\phi}_{T,out}}{\dot{\phi}_{T,in}} \quad (2.3.7)$$

Pump Torque

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

$$M_{T,pump,nom} = M_{T,pump}(v_{T,act}) \quad (2.3.8)$$

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

$$K_{T,scale} = \frac{\dot{\phi}_{T,in}}{\dot{\phi}_{T,p,n}} \quad (2.3.9)$$

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

$$M_{T,pump,act} = M_{T,pump,nom} \cdot K_{T, scale}^2 \quad (2.3.10)$$

Turbine Torque

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

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

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

$$M_{T,turb,act} = M_{T,pump,act} \cdot \mu_{T,act} \quad (2.3.12)$$

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].

$$M_{T,clutch,act} = M_{T,clutch,max} \cdot Z_T \quad (2.3.13)$$

Transmittable Torque

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

$$M_{T,trans} = M_{T,pump,act} + M_{T,clutch,act} \quad (2.3.14)$$

Detection of locked or unlocked clutch

The lock-up clutch will slide as long these conditions are fulfilled [2]:

$$[|M_{T,in} - M_{T,out}| \geq |M_T|] \nabla [\dot{\phi}_{T,rel} > 0] \vee [S_{T,act} > 0.8] \quad (2.3.15)$$

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

$$[|M_{T,in} - M_{T,out}| < |M_T|] \Delta [\dot{\phi}_{T,rel} < 0.01] \wedge [S_{T,act} < 0.8] \quad (2.3.16)$$

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

$\eta_{G,V,3}(N_G)$	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*.

$M_{G,V,3}(\dot{\phi}_{G,in}, N_G)$	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

$M_{G,V,4}(\dot{\phi}_{G,in}, N_G, T_G)$	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 $i = 1, \dots, 5$	°C
-----------	-------------------------------	----

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

$M_{G,V,5,i}(\dot{\varphi}_{G,in,i}, M_{G,in}, N_{G,i})$	Torque loss map temperature dependent $i = 1, \dots, 5$	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

$\dot{\varphi}_{G,in}$	Angular velocity on the drive side	rad/s
$\ddot{\varphi}_{G,in}$	Angular acceleration on the drive side	rad/s ²
$M_{G,in}$	Torque on the drive side	Nm
$\dot{\varphi}_{G,out}$	Angular velocity on the power take-off side	rad/s
$\ddot{\varphi}_{G,out}$	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	–
$\dot{\phi}_{G,out}$	Output Speed	rad/s
$M_{G,out}$	Output Torque	Nm
$\dot{\phi}_{G,in}$	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]:

$$i_{G,act} = i_G[N_{G,act}] \quad (2.4.1)$$

Angular Velocity and Acceleration

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

$$\dot{\phi}_{\text{out}} = \frac{\dot{\phi}_{\text{in}}}{i_{\text{G,act}}} \quad (2.4.2)$$

$$\ddot{\phi}_{\text{out}} = \frac{\ddot{\phi}_{\text{in}}}{i_{\text{G,act}}} \quad (2.4.3)$$

Inertia Moments

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

$$\Theta_{\text{G,in,act}} = \Theta_{\text{G,in}}[N_{\text{G,act}}] \quad (2.4.4)$$

$$\Theta_{\text{G,out,act}} = \Theta_{\text{G,out}}[N_{\text{G,act}}] \quad (2.4.5)$$

Torque Loss

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

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

$$M_{\text{G,loss}} = 0 \quad (2.4.6)$$

$$\eta_{\text{G}} = 1 \quad (2.4.7)$$

(2) **Calculation with use of the torque loss map** ($Z_{\text{G},i} = 2$)

The nominal loss moment is linear interpolated in the loss map [2]:

$$M_{\text{G,loss,nom}} = M_{\text{G,V},2}(\dot{\phi}_{\text{G,in}}; M_{\text{G,in}}; N_{\text{G,act}}) \quad (2.4.8)$$

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

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

The efficiency is now calculated as follows [2]:

$$\eta_{\text{G}} = 1 - \frac{M_{\text{G,loss,nom}}}{M_{\text{G,in}}} \quad (2.4.10)$$

- (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]:

$$M_{G,loss,n} = M_{G,V,3}(\dot{\phi}_{G,in}; N_{G,act}) \quad (2.4.11)$$

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

$$M_{G,loss,n} = M_{G,V,4}(\dot{\phi}_{G,in}; N_{G,act}; T_G) \quad (2.4.12)$$

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

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

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

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

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

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

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

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

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.

$\theta_{H,\text{in}}$	Inertia Moment on the drive side	kg m ²
$\theta_{H,\text{out}}$	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.

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

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

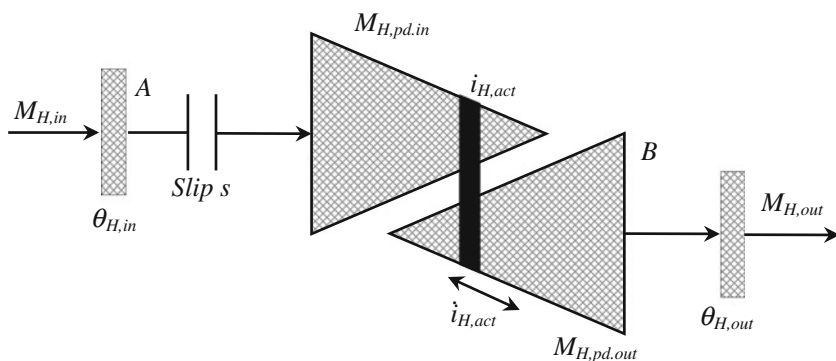


Fig. 2.6 Principle representation of a CVT gearbox [2]

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

$M_{H,V,1}(\dot{\varphi}_{H,in}, M_{H,in}, i_H)$	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 $i = 1, \dots, 5$	°C
-----------	-------------------------------	----

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

$M_{H,V,5,1}(\dot{\varphi}_{H,in,i}, M_{H,in,i}, N_{H,i})$	Torque loss map temperature dependent $i = 1, \dots, 5$	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
$T_H \dot{\phi}$	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
$\dot{\phi}_{H,in}$	Input speed	rad/s
$\ddot{\phi}_{H,in}$	Angular acceleration on the drive side	rad/s ²
$\dot{\phi}_{H,out}$	Output speed	rad/s
$\ddot{\phi}_{H,out}$	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
$\dot{\phi}_{H, ext}$	Speed External	rad/s

2.5.3.3 Data Output

$i_{H, act}$	Current Transmission Ratio	—
$N_{H, act}$	Current Gear	—
$\dot{\phi}_{H, in}$	Input Speed	rad/s
$M_{H, in}$	Input Torque	Nm
$\dot{\phi}_{H, out}$	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

$\Delta i_{H,act}$	Transmission gap in gear ratio	–
$M_{H,loss}$	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]:

$$\Delta i_{H,act} = i_{H,requ} - i_{H,act} \quad (2.5.1)$$

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]:

$$s_{H,act} = \frac{s_{H,diff}}{s_{H,ref}} \quad (2.5.2)$$

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

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].

$$\dot{\phi}_{ref} = \sqrt{\dot{\phi}_{break}^2 + (|\dot{\phi}_{Belt}| + |\Delta\dot{\phi}|)^2}$$

with $\dot{\phi}_{break} = 0.1$

$$\begin{aligned} \Delta\dot{\phi} &= \dot{\phi}_{H,in} - \dot{\phi}_{Belt} \\ \dot{\phi}_{Belt} &= \dot{\phi}_{H,out} \cdot i_{H,act} \\ s_H &= \frac{\Delta\dot{\phi}}{\dot{\phi}_{ref}} \end{aligned} \quad (2.5.4)$$

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]

$$M_{H,\text{loss}} = 0 \quad (2.5.5)$$

$$\eta_H = 1 \quad (2.5.6)$$

- (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].

$$M_{H,\text{loss,nom}} = M_{H,V,2}(\dot{\phi}_{H,\text{in}}; M_{H,\text{in}}; i_{H,\text{act}}) \quad (2.5.7)$$

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

$$M_{H,\text{loss,nom}} = M_{H,V,2}(\dot{\phi}_{H,\text{in}}; M_{H,\text{in}}; i_{H,\text{act}}) + M_{H,V,4}(\dot{\phi}_{H,\text{in}}; i_H; T_H) \quad (2.5.8)$$

$$\eta_H = 1 - \frac{M_{H,\text{loss,nom}}}{M_{H,\text{in}}} \quad (2.5.9)$$

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

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

- (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]:

$$M_{H,\text{loss,nom}} = M_{H,V,3}(\dot{\phi}_{H,\text{in}}; i_{H,\text{act}}) \quad (2.5.11)$$

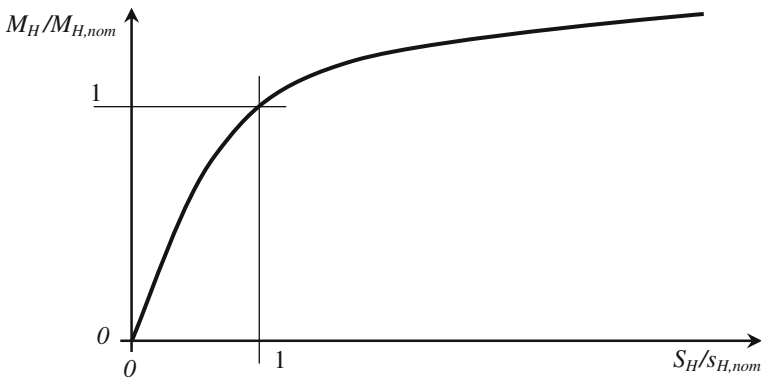


Fig. 2.7 Nominal loss moment variation [2]

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

$$M_{H,loss,nom} = M_{H,V,4}(\dot{\phi}_{H,in}; i_{H,act}; T_H) \quad (2.5.12)$$

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

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

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

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

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]:

$$M_{H,loss,nom} = M_{H,V,5}(T_H; i_{H,act}; \dot{\phi}_{H,in}; N_H) \quad (2.5.15)$$

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	–
-------	--------------------	---

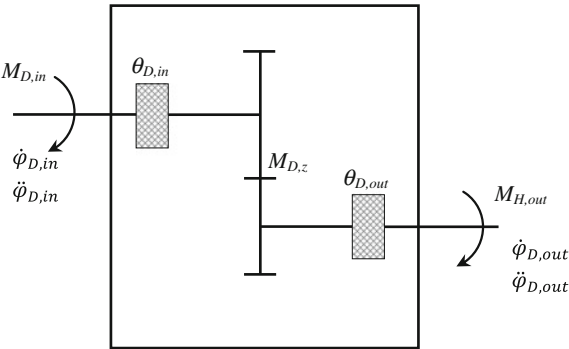
The overall ratio can be defined if this case of input is chosen in the properties.

$Z_{D,1}$	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.

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

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

Torque Loss Correction Temperature Dependent

$M_{D,V,4}(\dot{\phi}_{D,in}, T_D)$	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

$M_{D,V,2}(\dot{\phi}_{D,in}, M_{D,in})$	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 $i = 1, \dots, 5$	°C
-----------	-------------------------------	----

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

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

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

$\dot{\phi}_{D,out}$	Output Speed	rad/s
$M_{D,out}$	Output Torque	Nm
$\dot{\phi}_{D,in}$	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]

$$\dot{\varphi}_{D,out} = \frac{\dot{\varphi}_{D,in}}{i_D} \quad (2.6.1)$$

$$\ddot{\varphi}_{D,out} = \frac{\ddot{\varphi}_{D,in}}{i_D} \quad (2.6.2)$$

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]

$$M_{D,loss} = 0 \quad (2.6.3)$$

$$\eta_D = 1 \quad (2.6.4)$$

(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].

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

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

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

The efficiency is calculated as follows [2]:

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

(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]:

$$M_{D,loss,nom} = M_{D,V,3}(\dot{\phi}_{D,in}) \quad (2.6.8)$$

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

$$M_{D,loss,nom} = M_{D,V,4}(\dot{\phi}_{D,in}; T_D) \quad (2.6.9)$$

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

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

(4) **Calculation with use of the efficiency value ($Z_{D,i} = 4$)**

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

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

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].

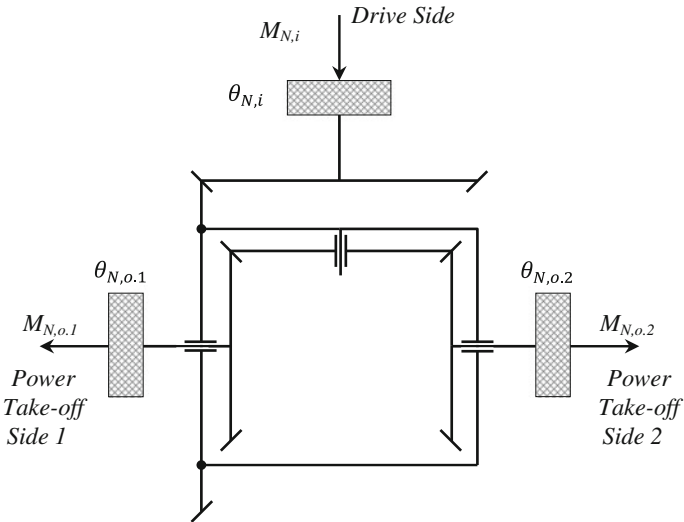


Fig. 2.9 Principle representation of a Differential [2]

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

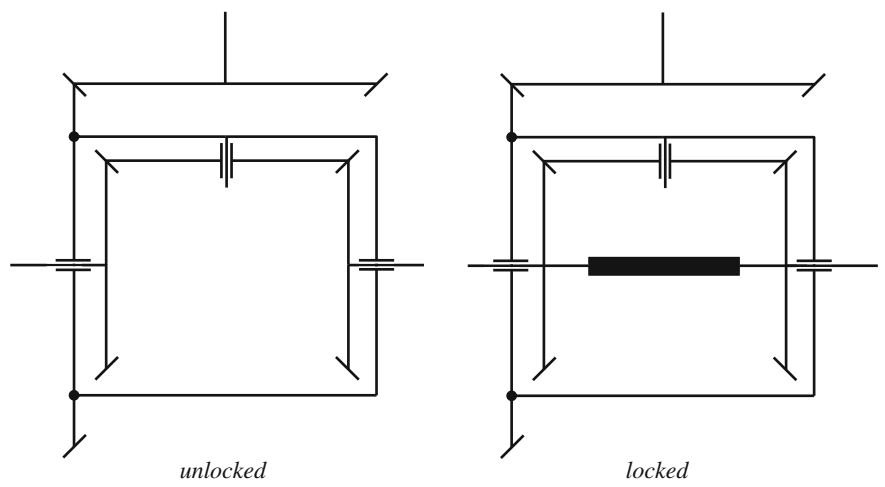


Fig. 2.10 Lock modes of Differential [2]

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

$\dot{\phi}_{N,in}$	Angular velocity on the drive side	rad/s
$\phi_{N,in}$	Angular acceleration on the drive side	rad/s ²
$M_{N,in}$	Torque on the drive side	Nm
$\dot{\phi}_{N,out,1(2)}$	Angular velocity on the power take-off side 1(2)	rad/s
$\phi_{N,out,1(2)}$	Angular acceleration on the power take-off side 1(2)	rad/s ²
$M_{N,out,1(2)}$	Torque on the power take-off side 1(2)	Nm

2.7.3.2 Data Input

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

2.7.3.3 Data Output

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

2.7.4 Computation Variables

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

2.7.5 Equation System

Gear Ratio

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

$$i_{N,inv} = \frac{1}{i_N} \quad (2.7.1)$$

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

$$i_{N,sum} = 1 + i_N \quad (2.7.2)$$

Split Equations

Unlocked differential

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

$$\dot{\phi}_{N,in} \cdot (i_n + 1) = \dot{\phi}_{N,out,1} + \dot{\phi}_{N,out,2} \cdot i_N \quad (2.7.3)$$

and for the lock moment [2]:

$$M_{N,lock} = 0 \quad (2.7.4)$$

Locked differential

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

$$\dot{\phi}_{N,out,1} = \dot{\phi}_{N,out,2} \quad (2.7.5)$$

The lock moment is defined as [2]:

$$M_{N,lock} = M_{N,out,1} - M_{N,out,2} \quad (2.7.6)$$

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 η 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

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

2.8.3.2 Data Output

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

(continued)

$\dot{\phi}_{PG,R}$	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]:

$$\dot{\phi}_{PG,S} - (1 + i_{PG,o}) \cdot \dot{\phi}_{PG,C} + i_{PG,o} \cdot \dot{\phi}_{PG,R} = 0 \quad (2.8.1)$$

Locked Planetary Gearbox

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

$$\dot{\phi}_{PG,S} = \dot{\phi}_{PG,C} = \dot{\phi}_{PG,R} \quad (2.8.2)$$

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

$$M_{PG,S} + M_{PG,C} + M_{PG,R} = 0 \quad (2.8.3)$$

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 CO₂ Emission

Performance, Consumption, Emission, and CO₂ 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 no 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

PT1-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	–
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This selection button has two positions:

- Gasoline
- Diesel

$Z_{E,charger}$	State indicator for charger type	–
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This selection button has three positions:

- *Without*: For the power correction on environment conditions it can be selected that a naturally aspirated 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
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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
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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.

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

$\dot{\phi}_{E,idle,base}$	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.

$\dot{\phi}_{E,SA,low}$	Lower Speed Border for Fuel Shut-Off	rpm
$\dot{\phi}_{E,SA,high}$	Upper Speed Border for Fuel Shut-Off	rpm
$\dot{\phi}_{E,SA,low,rel}$	Speed Difference Above Idle Speed for Lower Speed Limit	rpm
$\dot{\phi}_{E,SA,high,rel}$	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	–
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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
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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
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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

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

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

$\dot{\phi}_{E, idle}(T_E)$	Idle Speed	rpm
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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

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

$t_{E, ch, build-up}(\dot{\phi}_{E, out})$	Boost Pressure Build-up Time as Function of Speed	s
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This is the time the charger needs to build up the full boost pressure.

Boost Pressure

$p_{E, ch, idle}$	Boost Pressure at Idle	bar
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This value is required if the option “Boost Pressure at Idle” in the Properties window is activated.

$p_{E, ch}(\dot{\phi}_{E, out})$	Boost Pressure as absolute pressure	bar
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The boost pressure has to be defined as absolute pressure dependent on the engine speed.

BMEP Build-up Time

$t_{E, ch, BMEP, start}$	BMEP at Build-up Start	bar
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This is the engines BMEP at begin of BMEP build-up time.

$t_{E, ch, BMEP, stop}$	BMEP after Build-up Time, as percentages of maximum BMEP	%
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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.

$t_{E, ch, build-upBMEP}$	Constant BMEP Build-up Time	s
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This value has to be defined if the selection button **Response Behavior Turbo Charger** is set to *Constant BMEP Build-up Time*.

$t_{E, \text{ch. build-up BMEP}}(\dot{\phi}_{E, \text{out}})$	BMEP Build-up Time as function of speed	s
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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

$t_{E, \text{ch}}(\dot{\phi}_{E, \text{out}})$	Temperature behind charger	°C
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The temperature behind charger has to be defined as function of the engine speed.

Cooler Outlet Temperature

$t_{E, \text{IC}}(\dot{\phi}_{E, \text{out}})$	Temperature behind intercooler	°C
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The temperature behind intercooler has to be defined as function of the engine speed.

Basic Idle Maps

Idle Consumption Map

$b_{E, \text{idle}}(\dot{\phi}_{E, \text{out}}, p_{\text{eff}})$	Idle Consumption Map	l/h or kg/h
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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

$e_{E, \text{idle}, \text{NO}_x}(\dot{\phi}_{E, \text{out}}, p_{\text{eff}})$	Idle Emission Map NO _x	kg/h
$e_{E, \text{idle}, \text{CO}}(\dot{\phi}_{E, \text{out}}, p_{\text{eff}})$	Idle Emission Map CO	kg/h
$e_{E, \text{idle}, \text{HC}}(\dot{\phi}_{E, \text{out}}, p_{\text{eff}})$	Idle Emission Map HC	kg/h
$e_{E, \text{idle}, \text{Soot}}(\dot{\phi}_{E, \text{out}}, p_{\text{eff}})$	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*.

$e_{E, idle, O_2}(\dot{\varphi}_{E, out}, p_{eff})$	Idle Emission Map O ₂	kg/h
$e_{E, idle, H_2O}(\dot{\varphi}_{E, out}, p_{eff})$	Idle Emission Map H ₂ O	kg/h
$e_{E, idle, CO_2}(\dot{\varphi}_{E, out}, p_{eff})$	Idle Emission Map CO ₂	kg/h
$e_{E, idle, H_2}(\dot{\varphi}_{E, out}, p_{eff})$	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.

$e_{E, idle, exh}(\dot{\varphi}_{E, out}, p_{eff})$	Idle Exhaust Mass Flow Characteristic	kg/h
$T_{E, idle, exh}(\dot{\varphi}_{E, out}, p_{eff})$	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

$b_{E, h}(\dot{\varphi}_{E, out}, p_{eff})$	Fuel Consumption Map	l/h or kg/h
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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

$b_{E, spec}(\dot{\varphi}_{E, out}, p_{eff})$	Specific Fuel Consumption Map	l/kWh or kg/kWh
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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 ₂ O 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
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or

$M_{E,vk}(\dot{\varphi}_{E,out})$	Full Load Characteristic as torque	Nm
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or

$p_{E,eff,vk}(\dot{\varphi}_{E,out})$	Full Load Characteristic as BMEP	bar
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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	–
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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
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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
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or

$M_{E,vk,red,i}(\dot{\varphi}_{E,out})$	Gear dependent Full Load 1–5 as torque	Nm
---	--	----

or

$p_{E,eff,vk,red,i}(\dot{\varphi}_{E,out})$	Gear dependent Full Load 1–5 as BMEP	bar
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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:

$z_{E,red,geardep}$	Reduction Factor	–
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The associated gear dependent Full Load Characteristic is multiplied with this factor over the whole speed range.

$P_{E,vk,red,geardep}(\dot{\varphi}_{E,out})$	Gear dependent Full Load Reduction Characteristic 1–5	W
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The gear dependent full load reduction characteristics are subtracted from the associated gear dependent Full Load Characteristics.

Motoring Curve

Optionally:

$P_{E,sk}(\dot{\varphi}_{E,out})$	Motoring Curve as power	W
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or

$M_{E,sk}(\dot{\varphi}_{E,out})$	Motoring Curve as torque	Nm
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or

$p_{E,eff,sk}(\dot{\varphi}_{E,out})$	Motoring Curve as BMEP	bar
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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:

$P_{E,plc}[\omega_{E,out}]$	Engine Brake Curve as power	W
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or

$M_{E,plc}[\omega_{E,out}]$	Engine Brake Curve as torque	Nm
-----------------------------	------------------------------	----

or

$p_{E,plc}[\omega_{E,out}]$	Engine Brake Curve as mean pressure	Pa
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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

$I_{E,start,i}(t)$	Sequence of the Starter Current at the starting process, defined for up to 5 temperature levels	A
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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 be specified; the current is defined depending on time.

Load Signal Map

$\alpha_{E,th}(\dot{\phi}_{E,out}, p_{eff})$	Load Signal Map	%
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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

$\dot{\phi}_{E,out}$	Engine angular velocity on the power take-off side	rad/s
$\ddot{\phi}_{E,out}$	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	—
$\dot{\phi}_{E,idle}$	Idle Speed	rad/s
$K_{E,jake\ brake}$	Jake Brake Activation	—
$M_{E,desired}$	Desired Torque	Nm
$\dot{\phi}_{E,max}$	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
$e_{E,NO_x,act}$	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 ₂ O (instantaneous)	kg/s
T_E	Engine Temperature (instantaneous)	K
$K_{E,operate}$	Operation Control	—

(continued)

$\dot{\phi}_{E,out}$	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 $\dot{\phi}_{E,out}$	Pa
$p_{eff,sk}$	Brake mean pressure at Motoring Curve for $\dot{\phi}_{E,out}$	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 $\dot{\phi}$	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]:

$$M_{E,vk} = \frac{P_{E,vk}}{\dot{\phi}_{E,out}} \quad (2.9.1)$$

or as mean effective pressure [2]:

$$p_{eff,vk} = \frac{P_{E,vk} \cdot N_{E,stroke} \cdot \pi}{V_{E,h} \cdot \dot{\phi}_{E,out}} \quad (2.9.2)$$

A given Full Load Characteristic as moment results in the corresponding characteristic as power [2]:

$$P_{E,vk} = M_{E,vk} \cdot \dot{\phi}_{E,out} \quad (2.9.3)$$

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].

$$p_{\text{eff,vk}} = p_{\text{E,eff,vk}} \cdot z_{\text{E,red}} \quad (2.9.4)$$

Reduction curve

The reduction curve is subtracted from the full load curve [2].

$$p_{\text{eff,vk}} = p_{\text{E,eff,vk}} - p_{\text{E,eff,vk,red}} \quad (2.9.5)$$

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].

$$N_{\text{E,vk,red,i,high}} < N_{\text{G,act}} < N_{\text{E,vk,red,i,high}} \quad (2.9.6)$$

$$p_{\text{eff,vk}} = p_{\text{E,eff,vk,red,i}} \quad (2.9.7)$$

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 ($\dot{\varphi}_{\text{E,out}} < \dot{\varphi}_{\text{E,idle}}$) [2]:

$$k_{\text{E,operate}} = -1 \quad (2.9.8)$$

linear interpolation of $p_{\text{E,vk,help}}$ and $p_{\text{E,sk,help}}$ for $\dot{\varphi}_{\text{E,idle}}$ [2]:

$$\Delta p = p_{\text{E,vk,help}} - p_{\text{E,sk,help}} \quad (2.9.9)$$

$$p_{\text{eff,sk}} = -\frac{\Delta p}{\dot{\varphi}_{\text{E,idle}}} \cdot f_{\text{E,sk}} \cdot \dot{\varphi}_{\text{E,out}} + p_{\text{E,sk,help}} + \Delta p \cdot f_{\text{E,sk}} \quad (2.9.10)$$

$$p_{\text{eff,vk}} = p_{\text{eff,sk}} + \frac{\Delta p}{\dot{\varphi}_{\text{E,idle}}^3} \cdot (f_{\text{E,sk}} - 1) \cdot \dot{\varphi}_{\text{E,out}}^3 - \frac{\Delta p}{\dot{\varphi}_{\text{E,idle}}^2} \cdot (f_{\text{E,sk}} - 2) \cdot \dot{\varphi}_{\text{E,out}}^2 \quad (2.9.11)$$

$$f_{E,sk} = 1 (f_{E,sk} = 4 \text{ for automatic structure}) \quad (2.9.12)$$

(b) for an engine speed higher than maximum speed ($\dot{\phi}_{E,out} > \dot{\phi}_{E,max}$) [2]:

$$k_{E,operate} = 1 \quad (2.9.13)$$

linear interpolation of $p_{E,vk,help}$ and $p_{E,sk,help}$ for $\dot{\phi}_{E,max}$ [2]:

$$p_{eff,vk} = p_{E,vk,help} - |\dot{\phi}_{E,max} - \dot{\phi}_{E,out}| \cdot \frac{N_{E,stroke} \cdot \pi}{V_{E,h}} \quad (2.9.14)$$

$$p_{eff,sk} = p_{E,sk,help} - |\dot{\phi}_{E,max} - \dot{\phi}_{E,out}| \cdot \frac{N_{E,stroke} \cdot \pi}{V_{E,h}} \cdot f_{E,sk} \quad (2.9.15)$$

$$f_{E,sk} = 1 (f_{E,sk} = 0 \text{ for automatic structure}) \quad (2.9.16)$$

(c) for normal operating conditions ($\dot{\phi}_{E,idle} < \dot{\phi}_{E,out} < \dot{\phi}_{E,max}$) [2]:

$$k_{E,operate} = 0 \quad (2.9.17)$$

linear interpolation of $p_{eff,vk}$ and $p_{eff,sk}$ for $\dot{\phi}_{E,out}$

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]:

$$p_{E,env,dry,dyno} = p_{E,env,dyno} - R_{Wet} \cdot T_{E,env,dyno} \cdot \rho_{E,W,env,dyno} \quad (2.9.18)$$

with $R_{Wet} = 461,521 \text{ J/kg K}$

These conditions are also the inlet conditions [2]:

$$T_{E,inlet,dyno} = T_{E,env,dyno} \quad (2.9.19)$$

$$p_{E,inlet,dyno} = p_{E,env,dry,dyno} \quad (2.9.20)$$

(b) **Inlet Conditions at the Actual Driving Conditions**

First, the under the hood conditions have to be calculated [2]:

$$T_{E,Mot} = T_{U,air} + T_{E,diff,ub} \quad (2.9.21)$$

$$p_{E,Mot,dry} = p_{U,air} + p_{E,diff,ub} - R_{Wet} \cdot T_{E,Mot} \cdot \rho_{U,W} \quad (2.9.22)$$

The absolute humidity at environment conditions is calculated from the relative humidity using the following formulae [2]:

$$\rho_{U,W} = \frac{\varphi_{U,air} \cdot p'_W}{R_{Wet} \cdot T_{U,air}} \quad (2.9.23)$$

with [2]:

$$p'_W = 9.80665 \cdot e^{\left(58.73895 - \frac{6852.493}{T_{U,air}} - 5.262 \cdot \ln T_{U,air}\right)} \quad (2.9.24)$$

These underhood conditions are equal to the inlet conditions [2]:

$$T_{E,\text{inlet,act}} = T_{E,\text{Mot}} \quad (2.9.25)$$

$$p_{E,\text{inlet,act}} = p_{E,\text{Mot,dry}} \quad (2.9.26)$$

(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]:

$$f_A = A \cdot \left(\frac{p_{E,\text{inlet,act}}}{p_{E,\text{inlet,dyno}}} \right)^X \cdot \left(\frac{T_{E,\text{inlet,dyno}}}{T_{E,\text{inlet,act}}} \right)^Y + B \quad (2.9.27)$$

where the factors A, B, X, and Y depend on the engine and charger type.

- *Engine Factor*:

- For gasoline engines [2]:

$$f_m = 1 \quad (2.9.28)$$

- For diesel engines [2]:

Correct fuel delivery parameter [2]:

$$q_c = \frac{p_{E,\text{Mot}}}{p_{E,\text{inlet,act}}} \cdot 1000 \cdot \pi \cdot \frac{N_{E,\text{stroke}} \cdot b_{E,h,\text{act}}}{V_{E,h} \cdot \dot{\phi}_{E,\text{out}}} \quad (2.9.29)$$

$$(q_c < 40) \rightarrow f_m = 0.3$$

$$(40 \leq q_c \leq 65) \rightarrow f_m = 0.036 \cdot q_c - 1.14 \quad (2.9.30)$$

$$(q_c > 65) \rightarrow f_m = 1.2$$

- *Power Correction Factor* [2]:

$$\alpha_{\text{pow,corr}} = f_A^{f_m} \quad (2.9.31)$$

(d) **Power Correction**

With this power correction factor the Full Load Characteristic of the engine is reduced [2]:

$$p_{\text{eff,vk}} = p_{\text{eff,vk}} \cdot \alpha_{\text{pow,corr}} \quad (2.9.32)$$

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

$$p_{eff,theo} = p_{eff,sk} + (p_{eff,vk} - p_{eff,sk}) \cdot \alpha_{E,th} \quad (2.9.33)$$

Response Time [2]

$$\text{If } (p_{eff,theo} > p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}})$$

$$p_{eff,theo} = p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}} \quad (2.9.34)$$

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 from 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]:

$$T_{E,env,dyno} \quad \text{defined} \quad (2.9.35)$$

$$p_{E,env,dry,dyno} \quad \text{defined} \quad (2.9.36)$$

$$T_{E,Mot} = T_{E,env,dyno} \quad (2.9.37)$$

$$p_{E,Mot,dry} = p_{E,env,dry,dyno} \quad (2.9.38)$$

For calculation with power correction the conditions from the engine trunk has to be used [2]:

$$T_{E,Mot} \quad \text{from power correction} \quad (2.9.39)$$

$$p_{E,Mot,dry} \quad \text{from power correction} \quad (2.9.40)$$

$$T_{E,env,dyno} = T_{E,Mot} \quad (2.9.41)$$

$$p_{E,env,dry,dyno} = p_{E,Mot,dry} \quad (2.9.42)$$

The boost pressure increases after a response time, which is calculated as followed [2]:

$$p_{E,ch,over,dyno} = p_{E,inlet,dyno} - (p_{E,env,dyno} - R_{Wet} \cdot T_{E,inlet,dyno} \cdot \rho_{E,W,env,dyno}) \quad (2.9.43)$$

$$p_{E,ch,over,act} = p_{E,ch,over,dyno} + p_{E,ch,over,dyno} \cdot \frac{\Delta t}{t_{E,ch,build-up}} \quad (2.9.44)$$

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]

$\alpha_{E,th} = 0 \rightarrow$ Motoring Curve

$\alpha_{E,th} = 1 \rightarrow$ Full Load Characteristic

$$p_{eff,theo} = p_{eff,sk} + (p_{eff,vk} - p_{eff,sk}) \cdot \alpha_{E,th} \quad (2.9.45)$$

If the requested engine torque comes from the Data Bus as ‘Desired Torque,’ this value is directly converted into $p_{eff,theo}$ and then limited by $p_{eff,vk}$.

2.9.7.2 Response Time [2]

If $\left(p_{eff,theo} > p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}} \right)$

$$p_{eff,theo} = p_{eff,theo,old} + p_{eff,max} \cdot \frac{\Delta t}{t_{E,add}} \quad (2.9.46)$$

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]:

$$P_{E,\text{heat}} = b_{E,h,\text{act}} \cdot \rho_{E,\text{fuel}} \cdot H_{E,\text{fuel}} \quad (2.9.47)$$

The mechanical power take-off [2]:

$$P_{E,\text{act}} = M_{E,\text{act}} \cdot \dot{\phi}_{E,\text{out}} \quad (2.9.48)$$

The loss power in the exhaust emissions [2]:

$$P_{E,\text{emis}} = Z_{E,\text{EE}} \cdot (P_{E,\text{heat}} - P_{E,\text{act}}) \quad (2.9.49)$$

The rest energy has to go into the cooling system [2]:

$$P_{E,\text{cool}} = P_{E,\text{heat}} - P_{E,\text{act}} - P_{E,\text{emis}} \quad (2.9.50)$$

- 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
 $c_{E,v,\text{cool}}$ Heat capacity [J/K]

With a linear interpolation in the cooling characteristic, the value $c_{E,v,\text{cool}}$ is evaluated.

This value is transformed [2]:

$$\alpha_A = c_{E,v,\text{cool}} \cdot \left(1 + 0.4 \cdot \frac{v_{V,\text{act}}}{83} \right) \quad (2.9.51)$$

And the engine temperature can be calculated [2]:

$$T_E = T_E + \frac{(P_{E,\text{cool}} - \alpha_A \cdot (T_E - T_{W,\text{air}})) \cdot \Delta t_i}{m_{E,\text{eq}} \cdot c_{p,\text{H}_2\text{O}}} \quad (2.9.52)$$

where $c_{p,\text{H}_2\text{O}} = 4187 \frac{\text{J}}{\text{kg} \cdot \text{K}}$

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 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]:

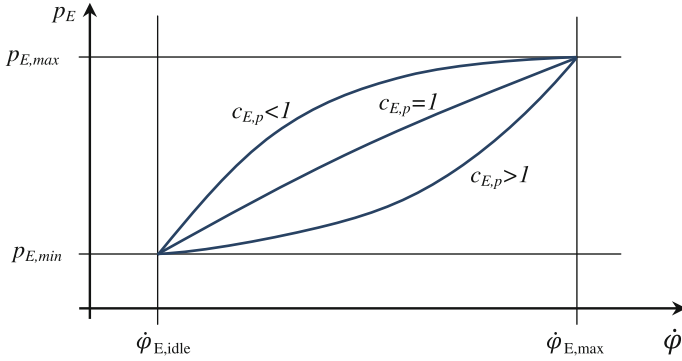


Fig. 2.11 Friction mean pressure [2]

$$f_B = \frac{p_{E,fric,max} - p_{E,fric,min}}{(\dot{\phi}_{E,max})^{c_{E,fric,p}} - (\dot{\phi}_{E,idle})^{c_{E,fric,p}}} \quad (2.9.53)$$

$$f_A = p_{E,fric,min} - f_B \cdot (\dot{\phi}_{E,idle})^{c_{E,fric,p}} \quad (2.9.54)$$

$$p_{E,fric,ref} = f_A + f_B \cdot |\dot{\phi}_{E,out}|^{c_{E,fric,p}} \quad (2.9.55)$$

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]:

$$f_{help} = 159.56 \cdot \ln \left| \frac{\eta_{E,40}}{1.8 \cdot 10^{-4}} \right| \quad (2.9.56)$$

$$\eta(T) = 1.8 \cdot 10^{-4} \cdot e^{\left(\frac{f_{help}}{1-273.15+95} \right)} \cdot e^{\left(\frac{-f_{help}}{887} \right)} \quad (2.9.57)$$

$$\eta_{E,act} = \eta(T_E) \eta_{E,ref} = \eta(T_{E,N}) \quad (2.9.58)$$

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:

$$p_{E,fric,add} = p_{E,fric,ref} \cdot \left(\left| \frac{\eta_{E,act}}{\eta_{E,ref}} \right|^{c_{E,fric,exp}} - 1 \right) \quad (2.9.59)$$

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

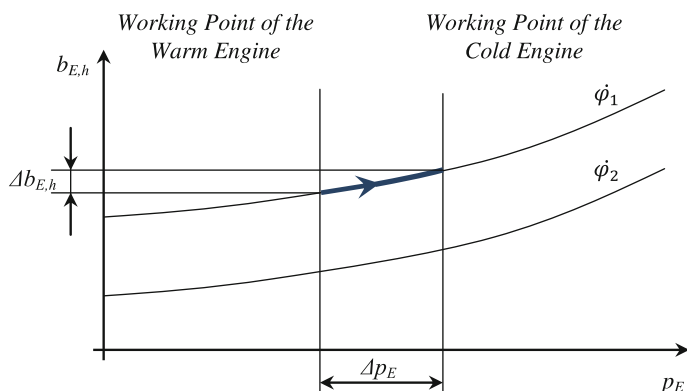


Fig. 2.12 Change of working point in the cold engine [2]

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 breaks 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 mean effective pressure can be expressed as follows [2]:

$$f_{mep} = c_{cb} \left(\frac{ND_b^3 L_b n_b}{B^2 s n_c} \right) + C_{cs} \left(\frac{D_b}{B^2 s n_c} \right) + c_{td} \left(\frac{N^2 D_b^2 n_b}{n_c} \right) \quad (2.9.60)$$

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]:

$$\begin{aligned} mep_{pb} = & c_{pb} \left(\frac{ND_b^3 L_b n_b}{B^2 S n_c} \right) + C_{ps} \left(\frac{V_p}{B} \right) + C_{pr} \left(1 + \frac{10^3}{N} \right) \left(\frac{1}{B^2} \right) \\ & C_o \cdot \frac{P_1}{P_a} \left(0.088 r_c + 0.182 r_c^{(1.33 - 2.38 \times 10^{-2} V_p)} \right) \end{aligned} \quad (2.9.61)$$

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]:

$$\begin{aligned} Fmep_{cv} = & c_{vb} \left(\frac{N n_b}{B^2 S n_c} \right) + c_{vo} + C_{vh} \left(\frac{L_v^{1.5} N^{0.5} n_v}{B S n_c} \right) \\ & + C_{vm} \left(1 + \frac{10^3}{N} \right) \frac{L_v n_v}{S n_c} + Fmep_{cam \text{ follower}} \end{aligned} \quad (2.9.62)$$

Flat Cam Follower [2]:

$$Fmep_{cam \text{ follower}} = C_{vf} \left(1 + \frac{10^3}{N} \right) \frac{n_v}{s n_c} \quad (2.9.63)$$

Roller Cam Follower [2]:

$$Fmep_{cam \text{ follower}} = C_{vr} \left(\frac{N n_v}{s n_c} \right) \quad (2.9.64)$$

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]:

$$Fmep_{aux} = \alpha + \beta N + \gamma N^2 \quad (2.9.65)$$

The constants α , β and γ are used to be 6.23×10^3 Pa, 5.22 Pa/rpm, -1.79×10^{-4} Pa/rpm², respectively.

B. Pumping Losses

The correlation used by Bohic has been used. That is [2]:

$$P_{mep} = 10^5 \frac{Disp}{0.0025} \cdot (0.0785 + 4.02 \times 10^{-5} N + 1.06 \times 10^{-8} N^2 + 4.64 \times 10^{-8} IMEP + 2.17 \times 10^{-10} N \times IMEP) \quad (2.9.66)$$

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].

$$\frac{Fmep T_{oil}}{Fmep T_{oil} = 90^\circ C} = \left(\frac{v T_{oil}}{v T_{oil} = 90^\circ C} \right)^{0.24} \quad (2.9.67)$$

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 $-30^\circ C$, 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]:

$$F_{mep_{crankshaft}} = c_{cb} \left(\frac{N^{0.6} D_b^3 L_b n_b}{B^2 S n_c} \right) \left(\frac{\mu}{\mu_{ref}} \right)^n + C_{cs} \left(\frac{D_b}{B^2 S n_c} \right) \quad (2.9.68)$$

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]:

$$F_{mep_{piston}} = \left(c_{pb} \left(\frac{N^{0.6} D_b^3 L_b n_b}{B^2 S n_c} \right) + C_{ps} \left(\frac{V_p^{0.5}}{B} \right) + C_{pr} \left(\frac{V_p^{0.5}}{B^2} \right) \right) \left(\frac{\mu}{\mu_{ref}} \right)^n \quad (2.9.69)$$

where:

C_{pb}	Coefficient for connecting rod bearing hydrodynamics	kPa/rpm ^{0.6} mm
C_{ps}	Coefficient for skirt-cylinder wall hydrodynamics	kPa mm ^{0.5} s ^{0.5}
C_{pr}	Coefficient for piston ring-cylinder wall	kPa mm ^{1.5} s ^{0.5}
n	Viscosity index (=0.4)	–

3. Valve Train

Means effective pressure due to the friction in the piston group is expressed as follows [2]:

$$\begin{aligned} F_{mep_{valvetrain}} = & c_{vb} \left(\frac{N^{0.6} n_b}{B^2 S n_c} \right) \left(\frac{\mu}{\mu_{ref}} \right)^n \\ & + C_{vs} + C_{vh} \left(\frac{L_v^{1.5} N^{0.5} n_v}{B S n_c} \right) \left(\frac{\mu}{\mu_{ref}} \right)^n + C_{vm} \left(2 + \frac{10}{5 + \mu N} \right) \frac{L_v n_v}{S n_c} \\ & + f_{mep_{cam/follower}} \end{aligned} \quad (2.9.70)$$

Flat cam follower [2]:

$$F_{mep_{cam\ follower}} = C_{vf} \left(2 + \frac{10}{5 + \mu N} \right) \frac{n_v}{S n_c} \quad (2.9.71)$$

Roller cam follower [2]:

$$F_{mep_{cam\ follower}} = C_{vr} \left(\frac{N n_v}{S n_c} \right) \quad (2.9.72)$$

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]

$$F_{mep_{aux}} = \alpha + (\beta N + \gamma N^2) \left(\frac{\mu}{\mu_{ref}} \right)^n \quad (2.9.73)$$

For oil pump, the constants α , β , γ & viscosity index (n) are: 1.28 kPa, 7.9×10^{-3} kPa mm³/rpm, -8.4×10^{-7} kPa mm³/rpm², 0.3 (viscosity index), respectively. For water pump α , β , γ & viscosity index (n) 0.13 kPa, 2×10^{-3} kPa mm³/rpm, 3×10^{-7} kPa mm³/rpm², 0.7, respectively. They are: 1.72 kPa, 6.9×10^{-4} kPa mm³/rpm, 1.2×10^{-7} kPa mm³/rpm², 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 $\dot{\phi}_{E,out}$ and the mean effective pressure $p_{eff,act}$ out of the fuel consumption map $b_{E,h}$ $\dot{\phi}_{E,out}$, p_E .

For ($\dot{\phi}_{E,out} < \dot{\phi}_{E,idle}$) and $\alpha_{th} < 0$, 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)	–
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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 $(\dot{\varphi}_{E,act} \leq \dot{\varphi}_{E,SA,low})$ and $Z_{E,SA,fc} = \text{activated}$ [2]:

$$b_{E,act} = b_{E,idle} - \frac{b_{E,idle} - b_{E,SA}}{\dot{\varphi}_{E,SA,low} - \dot{\varphi}_{E,idle}} \cdot (\dot{\varphi}_{E,act} - \dot{\varphi}_{E,idle}) \quad (2.9.74)$$

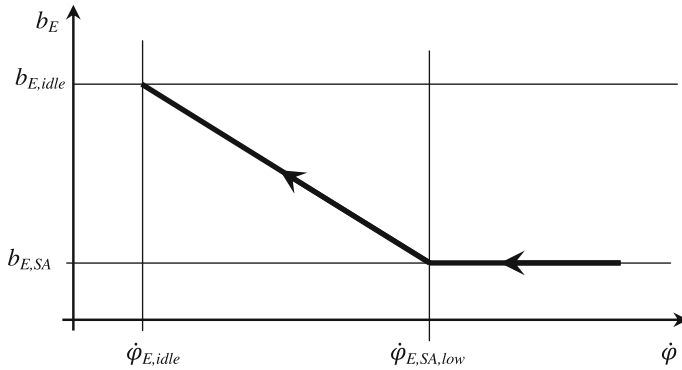


Fig. 2.13 Consumption increase after deactivation linear [2]

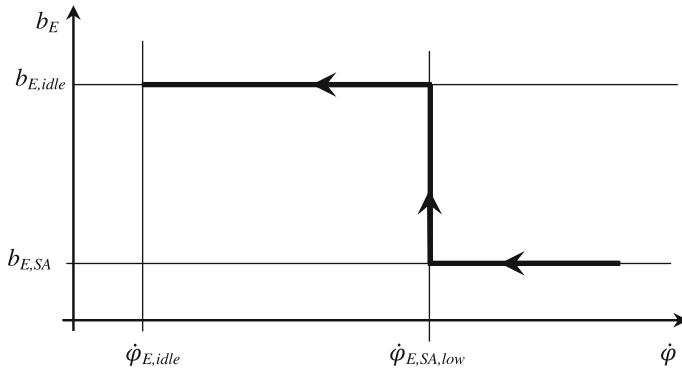


Fig. 2.14 Consumption increase after deactivation sharp rise [2]

(b) for $(\dot{\phi}_{E, act} > \dot{\phi}_{E, SA, low})$ [2]:

$$b_{E, act} = b_{E, SA} \quad (2.9.75)$$

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]:

$$f_{fuel} = \frac{b_{E, act}}{b_{E, h}} \quad (2.9.76)$$

The emissions are linear interpolated out of the maps for $\dot{\phi}_{E, act}$ and $P_{E, act}$.

This values out of the map have to be transformed with f_{fuel} [2]:

$$e_{\text{E,xx,act}} = e_{\text{E,xx}} \cdot f_{\text{fuel}} \quad (2.9.77)$$

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]:

$$Q_{\text{E,Q}} = Q_{\text{E,Q}} - \frac{0.5 \cdot (I_{\text{E,start}}(t_{i-1}) + I_{\text{E,start}}(t_{i+1}))}{(I_{\text{E,start}}(t_i) - I_{\text{E,start}}(t_{i-2}))} \quad (2.9.78)$$

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
------------	---------------------------------	-------------------

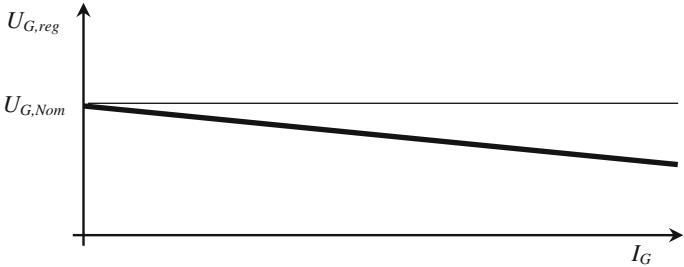


Fig. 2.15 Regulator voltage [2]

Idle Voltage

$R_{G,eq}$	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

$M_{L,pd,gen}(\dot{\varphi}_{L,gen})$	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

$I_{L,max}(\dot{\phi}_{L,gen})$	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

$\dot{\phi}_{L,in}$	Angular velocity on the drive side	rad/s
$\ddot{\phi}_{L,in}$	Angular acceleration on the drive side	rad/s ²
$M_{L,in}$	Torque on the drive side	Nm

2.10.3.2 Electrical Connections

$U_{L,net}$	Actual net voltage	V
I_L	Instantaneous generator current	A

2.10.3.3 Data Input

Z_L	Switch	–
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2.10.3.4 Data Output

$U_{L,net}$	Net Voltage	V
I_L	Current	A
$\dot{\phi}_{L,in}$	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
$\dot{\phi}_{L,cont}$	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 $U_{L,idle}(\dot{\phi}_{L,gen})$ and $I_{L,max}(\dot{\phi}_{L,gen})$

The minimum voltage is determined by the equation [2]:

$$U_{L,min,act} = U_{L,max,act} - \sqrt{\frac{I_{L,max,act}}{R_{G,eq}}} \quad (2.10.1)$$

(b) **For the controller voltage conditions**

The controller current and voltage $I_{L,max,cont}$, $U_{L,max,cont}$ for a given angular velocity $\dot{\phi}_{L,cont}$ is evaluated out of the maps $U_{L,idle}(\dot{\phi}_{L,cont})$ and $I_{L,max}(\dot{\phi}_{L,cont})$. The controller factor is defined as function of the controller current [2]:

$$C_{L,cont} = -R_{G,eq} \cdot \frac{1}{I_{L,max,cont}} \quad (2.10.2)$$

The minimum voltage fixed by the controller [2]:

$$U_{L,\min,\text{cont}} = U_{L,\max,\text{cont}} + C_{L,\text{cont}} \cdot I_{c,\max,\text{act}} \quad (2.10.3)$$

Now the program selects between three conditions:

- (a) For the generator area higher than the controller minimum voltage:
 $U_{L,\min,\text{cont}} \leq U_{L,\min,\text{act}} \rightarrow \text{Controller Characteristic}$
- (b) For generator voltage lower than the maximum controller voltage:
 $U_{L,\max,\text{cont}} \leq U_{L,\max,\text{act}} \rightarrow \text{Generator Characteristic}$
- (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]:

$$I_L = - \frac{(U_{L,\text{net}} - U_{L,\min,\text{cont}}) \cdot [1 - (U_{L,\text{net}} - U_{L,\max,\text{cont}})]}{C_{L,\text{cont}} \cdot (U_{L,\text{net}} - U_{L,\max,\text{cont}})} \quad (2.10.4)$$

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]:

$$I_L = -I_{L,\max,\text{act}} - R_{G,\text{equ}} \cdot \left(U_{L,\text{net}} - U_{L,\max,\text{act}} + \sqrt{\frac{I_{L,\max,\text{act}}^2}{R_{G,\text{equ}}}} \right)^2 \cdot (U_{L,\text{net}} - U_{L,\min,\text{act}}) \cdot [1 - (U_{L,\text{net}} - U_{L,\max,\text{act}})] \quad (2.10.5)$$

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]:

$$U_{L,\text{switch}} = -\frac{b}{2 \cdot a} + \sqrt{\frac{b^2 - 4 \cdot a \cdot c}{2 \cdot a}} \quad (2.10.6)$$

$$a = -R_{G,\text{equ}} \quad (2.10.7)$$

$$b = -2 \cdot \left(-U_{L,\max,\text{act}} + \sqrt{\frac{I_{L,\max,\text{act}}}{R_{G,\text{equ}}}} \right) \cdot R_{G,\text{equ}} - \frac{1}{C_{L,\text{cont}}} \quad (2.10.8)$$

$$c = I_{C,\max,\text{act}} \cdot R_{G,\text{equ}} \cdot \left(-U_{L,\max,\text{act}} + \sqrt{\frac{I_{L,\max,\text{act}}}{R_{G,\text{equ}}}} \right)^2 + \frac{U_{L,\max,\text{cont}}}{C_{L,\text{cont}}} \quad (2.10.9)$$

If the net voltage is lower than the switch voltage:

$U_{L,\text{net}} < U_{L,\text{switch}} \rightarrow$ Generator Characteristic

else

$U_{L,\text{net}} \geq U_{L,\text{switch}} \rightarrow$ Controller Characteristic

Efficiency

The generator efficiency $\eta_{L,\text{act}}$ 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 $M_{L,\text{pd},\text{act}}$ is interpolated out of the loss function.

Thus, we can write the equation for the whole generator torque [2]:

$$M_{L,\text{in}} = M_{L,\text{pt},\text{act}} - \frac{I_L \cdot U_{L,\text{net}}}{Z_L \cdot \dot{\phi}_{L,\text{in}}} \quad (2.10.10)$$

(b) Evaluation with efficiency value

The overall efficiency value $\eta_{L,\text{act}}$ 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]:

$$M_{L,\text{in}} = - \frac{1}{\eta_{L,\text{act}}} \cdot \frac{I_L \cdot U_{L,\text{net}}}{\eta_{L,\text{el}} \cdot \dot{\phi}_{L,\text{in}}} \quad (2.10.11)$$

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*.

$R_x(setValue_X)$	Resistance as function of Set Value X	Ω
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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 (U_x, 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]:

$$I_X = \frac{U_{X,net}}{R_{X,act}} \quad (2.11.1)$$

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 $U_1, \dots, U_5$

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
------------	--------------------------------------	-------------------

$\dot{\phi}_{J,min}$	Minimum Speed	rad/s
----------------------	---------------	-------

The minimum speed is the minimum angular velocity the electric motor can run at.

$\dot{\phi}_{J,max}$	Maximum Speed	rad/s
----------------------	---------------	-------

The maximum speed is the maximum angular velocity the electric motor can run at.

$U_{J,nom}$	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*.

$M_J(\dot{\phi}_{J,out}, U_J)$	Torque–Voltage Map of Motor	Nm
--------------------------------	-----------------------------	----

Map of the output torque dependent on the speed and the voltage.

$I_J(\dot{\phi}_{J,out}, U_J)$	Current–Voltage Map of Motor	A
--------------------------------	------------------------------	---

Map of the absorbed current dependent on the speed and the voltage.

$\eta_J(\dot{\phi}_{J,out}, U_J)$	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.

$\eta_{J,i}(\dot{\phi}_{J,out,i}, P_{J,i})$	Load-dependent Efficiency Maps $i = 1, \dots, 5$	–
---	--	---

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.

$I_J(\dot{\phi}_{J,out})$	Idle Current Curve	A
---------------------------	--------------------	---

Curve of the absorbed current dependent on the idle speed.

$I_{J,A}(\theta_{J,out})$	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

$\dot{\phi}_{J,out}$	Angular velocity of the motor	rad/s
$\ddot{\phi}_{J,out}$	Angular acceleration of the motor	rad/s ²
$M_{J,out}$	Instantaneous motor torque	Nm

2.12.3.2 Electrical Connections

$U_{J,net}$	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

$K_{J,act}$	Operation Control	–
$U_{J,net}$	Net Voltage	V
$\dot{\phi}_{J,out}$	Speed	rad/s
$M_{J,out}$	Electric Motor Torque	Nm
Q_J	Energy Consumption	As
I_J	Current	A
P_J	Mechanical Power	W
$P_{J,loss}$	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]:

$$M_{J,act} = M(n_{act}, U_{act}) \cdot \alpha_J \quad (2.12.1)$$

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]:

$$P_{J,mech,act} = M_{J,act} \cdot n_{act} \quad (2.12.2)$$

2.12.5.2 Electrical Part

Current–Voltage Map

Calculation of the actual current by the current–voltage map [2]:

$$I_{J,act} = I(n_{act}, U_{J,net}) \cdot abs(\alpha_J) \quad (2.12.3)$$

Constant Efficiency Value

Calculation by efficiency value, idle current map, and starting current map. Actual electrical power [2]:

$$P_{J,el,act} = \frac{P_{J,mech,act}}{\eta_J} \quad n \neq 0, \quad M \neq 0 \quad (2.12.4)$$

Actual current of the motor [2]:

$$I_{J,act} = \frac{P_{J,el,act}}{U_{J,act}}. \quad (2.12.5)$$

Special cases:

$n = 0, M = 0 \rightarrow I_{act} = 0$.

$n \neq 0, M = 0 \rightarrow$ by the idle current curve: $I_{J,act} = I(n_{act})$.

$n = 0, M \neq 0 \rightarrow$ by the starting current curve: $I_{J,act} = I(M_{J,act})$.

Efficiency Map

Calculation of the actual power and the actual current by the efficiency map and the starting current [2]:

$$P_{J,el,act} = \frac{P_{J,mech,act}}{\eta_{J,act}} \quad (2.12.6)$$

with $\eta_{J,act} = \eta(n_{act}, U_{act})$ with $n \neq 0$ [2]:

$$I_{J,act} = \frac{P_{J,el,act}}{U_{J,act}} \quad (2.12.7)$$

Special case [2]:

$$n = 0 \rightarrow I_{J,act} = I_{J,A}. \quad (2.12.8)$$

Load-dependent efficiency maps

There are maps for certain load levels.

$\eta = f(n, P_{J,mech})$, each $U_1, \dots, U_5$ can be optionally defined.

Determination of the electrical power [2]:

$$P_{J,el,act} = \frac{P_{J,mech,act}}{\eta_{J,act}} \quad (2.12.9)$$

whereas $\eta_{J,act}$ is calculated as follows:

For those (two) voltage levels with $U_j \leq U_{J,act} \leq U_k$ the $\eta_{j,act}$ and $\eta_{k,act}$ are calculated.

These values are used for the interpolation of $\eta_{j,\text{act}}$.
The current is defined by [2]:

$$I_{j,\text{act}} = \frac{P_{j,\text{el,act}}}{U_{j,\text{act}}} \quad (2.12.10)$$

Special cases:

$n = 0, M = 0 \rightarrow I_{j,\text{act}} = 0.$

$n = 0, M \neq 0 \rightarrow$ by the starting current curve: $I_{j,\text{act}} = I(M_{j,\text{act}}).$

$n \neq 0, M = 0 \rightarrow$ by the idle current curve: $I_{j,\text{act}} = I(n_{\text{act}}).$

Definitions of Idle and Starting

Minimal angular velocity $\dot{\phi}_{\min}$ maximal angular velocity $\dot{\phi}_{\max}$... are given by the user; Minimal torque $M_{\min}$, maximal torque $M_{\max}$... are determined by the torque map $M_J(\dot{\phi}_{J,\text{out}}, U_J)$

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 $\dot{\phi}_0 = \dot{\phi}_{\max} \cdot 0.01$

When $\dot{\phi}_{\text{act}} = \dot{\phi}_0$ 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 $M_{\text{act}} < M_0$, 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 $U_2, \dots, U_5$

When these switches are deactivated, the user can enter the characteristic maps only for one user-defined constant voltage level U_1 . If the user activates some of the switches $U_2 \dots U_5$, 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 $U_2 \dots U_5$ (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	–
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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	–
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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

$\dot{\phi}_{EM,mot,max}$	Maximum Speed	1/min
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The maximum speed is the maximum angular velocity the electric motor can run at.

$M_{EM,drag}$	Drag Torque	Nm
$I_{EM,gen,max}$	Maximum Current–Generator	A

Thermal Model

m_{EM}	Mass of Machine	kg
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$T_{EM,init}$	Initial Temperature	°C
---------------	---------------------	----

This is the temperature which the electric machine has at calculation start.

$\alpha_{EM,th}$	Specific Heat Transition	W/K
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The specific heat transition sums up all influences (such as material, surface state etc.), which influence the transmission of heat.

$t_{EM,T}$	Thermal Time Constant of Maximum Power	s
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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.

$T_{EM,max}$	Maximum Temperature	°C
$C_{EM,th}$	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).

$T_{EM,L}$	Layout Temperature	°C
------------	--------------------	----

The layout temperature is the temperature where the electric machine has its highest efficiency.

$\beta_{EM,Rem}$	Temperature Coefficient of Remanence Induction	1/K
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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
$P_{EM,U_{EM,max}}(\dot{\varphi}_{EM,out})$	Maximum Power (Torque) mechanical	kW

Either the maximum mechanical power or the maximum mechanical torque is defined as function of the machine's speed.

$\eta_{EM}(P_{EM,U_{EM,act}},\varphi_{EM,out})$	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*.

$P_{EM,loss}(P_{EM,U_{EM,act}},\varphi_{EM,out})$	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
$\phi_{EM,out}$	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	–
$K_{EM,overflow}$	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]:

$$M_{EM,dt} = M_{EM} - \Theta_{EM,nom} \ddot{\phi}_{EM,out} \quad (2.13.1)$$

The following calculation is used for permanent field machines [2]:

$$M_{EM}(T_{EM}) = (1 + \beta_{EM,REm}(T_{EM} - T_{EM,L}))M_{EM}(T_{EM,L}) \quad (2.13.2)$$

(drivetrain turned off) [2]

$$M_{EM} = M_{EM,drag} (\dot{\phi}_{EM} / \dot{\phi}_{EM,max})^2 \quad (2.13.3)$$

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].

$$M_{EM} = kM_{EM,max,mot}, \quad \text{if } k > 0, \quad (2.13.4)$$

$$M_{EM} = (-k)M_{EM,max,gen}, \quad \text{otherwise.}$$

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]:

$$P_{EM,el} = P_{EM,mech} + P_{EM,loss}. \quad (2.13.5)$$

The loss of power $P_{EM,loss}$ 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]:

$$P_{EM,mech} = \dot{\phi}_{EM} M_{EM} \quad (2.13.6)$$

There are the following conventions of the sign:

If $P_{EM,el} > 0$, then the motor-related mode is chosen, else if $P_{EM,el} < 0$, 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 $\dot{\phi}_{EM,1}$ are the smallest data points in the characteristic map of the machine.

Motor-related losses [2]

If $M_{EM,out} > M_{EM,1}$, $\dot{\phi}_{EM,out} > \dot{\phi}_{EM,1}$

$$P_{EM,loss,act} = P_{EM,mech,act} \left(\frac{1}{\eta_{EM}} (M_{EM,out}, \dot{\phi}_{EM,out}) - 1 \right) \quad (2.13.7)$$

If $M_{EM,out} > M_{EM,1}$, $0 < \dot{\phi}_{EM,out} \leq \dot{\phi}_{EM,1}$

$$P_{EM,loss,act} = \dot{\phi}_{EM,out,1} M_{EM,1} \left(\frac{1}{\eta_{EM}} (M_{EM,out}, \dot{\phi}_{EM,out}) - 1 \right) \quad (2.13.8)$$

Generator-related losses [2]

If $M_{EM,1} > |M_{EM,drag}|$, then $M_{EM,1}$ is set to $M_{EM,drag}$.

If $|M_{EM}| \gg 0$, $\dot{\phi}_{EM} \gg 0$

$$P_{EM,loss} = |P_{EM,mech}(1 - \eta_{EM}(M_{EM}, \dot{\phi}_{EM}))| \quad (2.13.9)$$

If $|M_{EM}| \gg 0$, $\dot{\phi}_{EM} \cong 0$

$$P_{EM,loss} = |\dot{\phi}_{EM,1} M_{EM}(1 - \eta_{EM}(M_{EM}, \dot{\phi}_{EM}))| \quad (2.13.10)$$

Losses due to small torque [2]

If $M_{EM,out} \gg 0$, $\dot{\phi}_{EM,out} \gg 0$

$$P_{EM,loss} = \dot{\phi}_{EM} M_{EM,1} \left[a(M_{EM}) \left(\frac{1}{\eta_{EM}} (M_{EM,1}, \dot{\phi}_{EM}) - 1 \right) + (1 - a(M_{EM})) (1 - \eta_{EM}(M_{EM,1}, \dot{\phi}_{EM})) \right] \quad (2.13.11)$$

If $M_{EM,out} \gg 0$, $\dot{\phi}_{EM,out} \cong 0$

$$P_{EM,loss} = \dot{\phi}_{EM} M_{EM,1} \left[a(M_{EM}) \left(\frac{1}{\eta_{EM}} (M_{EM,1}, \dot{\phi}_{EM,1}) - 1 \right) + (1 - a(M_{EM})) (1 - \eta_{EM}(M_{EM,1}, \dot{\phi}_{EM,1})) \right] \quad (2.13.12)$$

where

$$a(M_{EM}) = (M_{EM} - M_{EM,drag} \dot{\phi}_{EM}^2) / (M_{EM,1} - M_{EM,drag} \dot{\phi}_{EM}^2) \quad (2.13.13)$$

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]:

$$I_{EM} = P_{EM,el}/U_{EM,net} \quad (2.13.14)$$

For the maximal torque the following is defined using the loss of power and [2]:

$$R_{th} = 1/\alpha_{EM,th} \quad (2.13.15)$$

$$I_{EM} = P_{EM,el}/U_{EM,net} \quad (2.13.16)$$

$$P_{EM,loss,max} = (T_{EM} - T_{EM,env} + (T_{EM,max} - T_{EM})/(1 - \exp(-1(t_{EM,T}/(C_{EM,th}R_{th})))))/R_{th}. \quad (2.13.17)$$

$$M_{EM,max,mot} = M_{EM,max,mot}(P_{EM,loss,max}, I_{EM,mot,max}) \quad (2.13.18)$$

$$M_{EM,max,gen} = M_{EM,max,gen}(P_{EM,loss,max}, I_{EM,gen,max}) \quad (2.13.19)$$

Here the complete Characteristic Map is being searched beginning at the maximal permitted torque, until the loss of power is smaller than $P_{EM,loss,max}$. 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]:

$$M_{EM,max} = P_{EM,U_{EM,max}}(\dot{\varphi}_{EM})/\dot{\varphi}_{EM} \quad (2.13.20)$$

2.13.5.3 Thermal Part

The basic equations of the transition of heat in the electric machine are [2]:

$$dQ = m_{EM}C_{EM,th} dT = /P_{EM,W}dt \quad (2.13.21)$$

$P_{EM,W}$ 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]:

$$P_W = P_{EM,loss} + P_{EM,env} \quad (2.13.22)$$

and [2]:

$$P_{EM,env} = \alpha_{EM,th}(T_{EM} - T_{EM,env}) \quad (2.13.23)$$

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
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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
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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 $i = 1, \dots, 5$	°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 $i = 1, \dots, 5$	V
$U_{QH,idle,discharge,i}(Q_{QH,act})$	Idle Voltage—Discharge $i = 1, \dots, 5$	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 $i = , \dots, 5$	Ohm
$R_{QH,discharge,i}(Q_{QH,act})$	Ohmic Resistance—Discharge $i = , \dots, 5$	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 $i = 1, \dots, 5$	%
----------------------------------	---	---

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 $i = , \dots, 5$	Ohm
$R_{QH,conc,discharge,i}(Q_{QH,act})$	Resistance of RC Concentration Overvoltage—Discharge $i = , \dots, 5$	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 $i = , \dots, 5$	Ohm
$R_{QH,trans,discharge,i}(Q_{QH,act})$	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
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(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]:

$$U_{QH,terminal} = U_{QH,idle}(I_{QH,terminal}, SOC) - I_{QH,ohmic} \cdot R_{QH}(I_{QH,terminal}) - Q_{QH,conc}/C_{QH,conc} - Q_{QH,trans}/C_{QH,trans} \quad (2.14.1)$$

$$I_{QH,ohmic,trans} = Q_{QH,trans}/(C_{QH,trans} \cdot R_{QH,trans}) \quad (2.14.2)$$

$$I_{QH,ohmic,conc} = Q_{QH,conc}/(C_{QH,conc} \cdot R_{QH,conc}) \quad (2.14.3)$$

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]:

$$I_{QH,max,charge} = (U_{QH,idle,charge}(I_{QH,terminal}, SOC) - U_{QH,max} - Q_{QH,conc}/C_{QH,conc} - Q_{QH,trans}/C_{QH,trans})/R_{QH}(I_{QH,terminal}). \quad (2.14.4)$$

and [2]:

$$I_{QH,max,discharge} = (U_{QH,idle,discharge}(I_{QH,terminal}, SOC) - U_{QH,min,discharge} - Q_{QH,conc}/C_{QH,conc} - Q_{QH,trans}/C_{QH,trans})/R_{QH}(I_{QH,terminal}) \quad (2.14.5)$$

with [2]:

$$SOC_{QH} = Q_{QH}/Q_{QH,max} \quad (2.14.6)$$

The initial values are calculated by [2]:

$$Q_{QH,init} = SOC_{QH,init} \cdot Q_{QH,max} \quad (2.14.7)$$

The maximum power in and maximum power out are calculated in a numerical way by searching for the maximum within the functions [2]:

$$P_{QH,out,max}(U_{QH,min,discharge}, I_{QH,terminal}) \text{ and } P_{QH,in,max}(U_{QH,max,charge}, I_{QH,terminal})$$

2.14.5.2 Thermal Equations

The basic equation for the heating within a material is [2]:

$$dQ = m_{QH,cell} \cdot C_{QH,heat} dT_{QH,bat} = P_{QH,th} dt \quad (2.14.8)$$

Here, $P_{QH,th}$ 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]:

$$P_{QH,th} = P_{QH,th,el} + P_{QH,th,ambient} \quad (2.14.9)$$

and it is [2]:

$$P_{QH,th,ambient} = \alpha_{QH,th,trans} (T_{QH,bat} - T_{QH,ambient}) \quad (2.14.10)$$

and [2]:

$$\begin{aligned} P_{QH,th,el} = & I_{QH,ohmic}^2 \cdot R_{QH} + I_{QH,ohmic,trans}^2 \cdot R_{QH,trans} + I_{QH,conc}^2 (T_{QH,act}) \cdot R_{QH,conc} \\ & + |0.5 I_{QH,terminal} \cdot (U_{QH,idle} (I_{QH,terminal} \cdot SOC_{QH}) - U_{QH,idle} (-I_{QH,terminal}, SOC_{QH}))| \end{aligned} \quad (2.14.11)$$

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
$\phi_{\text{ref,act}}$	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]:

$$\text{If } (j_{G,\text{target}} \geq j_{G,\text{act}}) \rightarrow j_{G,\text{new,up}} = j_{G,\text{target}} \quad (2.15.1)$$

$$\text{If } (j_{G,\text{target}} \leq j_{G,\text{act}}) \rightarrow j_{G,\text{new,dn}} = j_{G,\text{target}} \quad (2.15.2)$$

2.15.5.2 Velocity Shifting

The reference is the vehicle velocity [2].

$$\text{If } (j_{G,\text{act}} < N_G) \wedge (V_{v,\text{act}} \geq V_{o,\text{incr}} \lfloor j_{G,\text{act}} \rfloor) \rightarrow j_{G,\text{new,up}} = j_{G,\text{act}} + 1 \quad (2.15.3)$$

$$\text{If } (j_{G,\text{act}} > 1) \wedge (V_{v,\text{act}} \leq V_{o,\text{decv}} \lfloor j_{G,\text{act}} \rfloor) \rightarrow j_{G,\text{new,dn}} = j_{G,\text{act}} - 1 \quad (2.15.4)$$

2.15.5.3 Speed Shifting

Each angular velocity could be selected via Data Bus for the reference speed [2].

$$\text{If } (j_{G,\text{act}} < N_G) \wedge (\dot{\phi}_{\text{ref,act}} \geq \dot{\phi}_{o,\text{incr}} \lfloor j_{G,\text{act}} \rfloor) \rightarrow j_{G,\text{new,up}} = j_{G,\text{act}} + 1 \quad (2.15.5)$$

$$\text{If } (j_{G,\text{act}} > 1) \wedge (\dot{\phi}_{\text{ref,act}} \leq \dot{\phi}_{o,\text{deu}} \lfloor j_{G,\text{act}} \rfloor) \rightarrow j_{G,\text{new,dn}} = j_{G,\text{act}} - 1 \quad (2.15.6)$$

2.15.5.4 Program Shifting

The shifting information is taken from the shifting program.

For up- and downshifting [2]:

$$\text{If } (j_{G,\text{prog}} \geq j_{G,\text{act}}) \rightarrow j_{G,\text{new,up}} = j_{G,\text{prog}} \quad (2.15.7)$$

$$\text{If } (j_{G,\text{prog}} \leq j_{G,\text{act}}) \rightarrow j_{G,\text{new,dn}} = j_{G,\text{prog}} \quad (2.15.8)$$

The new gear position is chosen as follows [2]:

$$\text{If } (j_{G,\text{new,up}} \geq j_{G,\text{act}} + 1) \rightarrow j_{G,\text{new}} = j_{G,\text{act}} + 1 \quad (2.15.9)$$

$$\text{else if } (j_{G,\text{new,dn}} \leq j_{G,\text{act}} - 1) \rightarrow j_{G,\text{new}} = j_{G,\text{act}} - 1 \quad (2.15.10)$$

$$\text{else} \rightarrow j_{G,\text{new}} = j_{G,\text{act}} \quad (2.15.11)$$

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

$\dot{\phi}_{P,incr} [n, \alpha_{E,dk}]$ or $v_{P,incr} [n, \alpha_{E,dk}]$	Upshifting Speed (Velocity) dependent on the gear and the load signal	rpm or km/h
$\dot{\phi}_{P,decr} [n, \alpha_{E,dk}]$ or $v_{P,decr} [n, \alpha_{E,dk}]$	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

$\dot{\phi}_{P,incr}[n, \alpha_{E,dk}]$ 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
$\dot{\phi}_{P,decr}[n, \alpha_{E,dk}]$ 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.

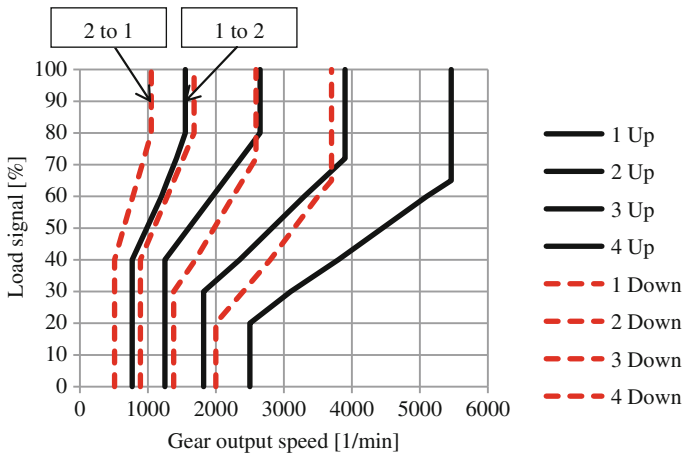


Fig. 2.16 Gear shifting map example. (dashed red down shifting, black up shifting) [2]

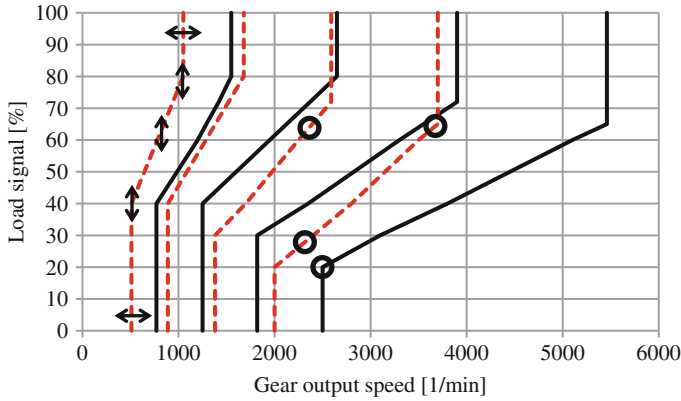


Fig. 2.17 Restrictions in the Gear Shifting Program [2]

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]:

$$J = \text{afc} + \beta_1 \int_{\text{time}} (v_{\text{actual}} - v_{\text{desired}})^2 dt + \beta_2 \int_{\text{time}} |\text{gear}'| dt + \beta_3 \int_{\text{time}} |\text{acceleration}'| dt. \quad (2.16.1)$$

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 Schittkowski) is used which is described shortly below.

NLPQL solves smooth nonlinear problems under nonlinear equality and inequality constraints, i.e. [2]:

$$\min f(\mathbf{x})$$

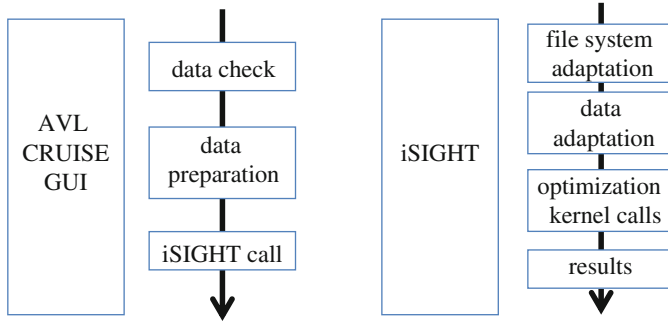


Fig. 2.18 iSIGHT is called for optimization in AVL CRUISE [2]

$$x \in \mathbb{R}^n : g_j(x) = 0, j = 1, \dots, m_e \quad (2.16.2)$$

$$g_j(x) \geq 0, j = m_e + 1, \dots, m$$

$$x_l \leq x \leq x_u$$

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]:

$$L(x, u) := f(x) - \sum_{j=1}^m u_j g_j(x). \quad (2.16.3)$$

quadratically, where $x \in \mathbb{R}^n$, and where $u = (u_1, \dots, u_m)^T \in \mathbb{R}^m$ is the multiplier vector.

To formulate the quadratic subproblem, it will be proceeded from given iterates $x_k \in \mathbb{R}^n$, an approximation of the solution, $v_k \in \mathbb{R}^m$ and approximation of the multipliers, and $B_k \in \mathbb{R}^{n \times n}$ an approximation of the Hessian of the Lagrangian function.

Then the following quadratic programming problem has to be solved [2]:

$$\min \frac{1}{2} d^T B_k d + \nabla f(x_k)^T d \quad (2.16.4)$$

$d \in \mathbf{R}^n : \nabla g_j(x_k)^T d + g_j(x_k) = 0, j = 1, \dots, m_e$
 $\nabla g_j(x_k)^T d + g_j(x_k) \geq 0, j = m_e, \dots, m..$ Let $\mathbf{d}_k$ be the optimal solution and u_k the corresponding multiplier. A new iterate is obtained by [2]:

$$\begin{pmatrix} x_{k+1} \\ v_{k+1} \end{pmatrix} := \begin{pmatrix} x_k \\ v_k \end{pmatrix} + \alpha_k \begin{pmatrix} \mathbf{d}_k \\ u_k - v_k \end{pmatrix} \quad (2.16.5)$$

where $\alpha_k \in (0, 1]$ is a suitable steplength parameter.

An SQP method is identical to Newton'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 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]:

$$q_k := \nabla_x L(x_{k+1}, u_k) - \nabla_x L(x_k, u_k) \quad (2.16.6)$$

$$w_k := x_{k+1} - x_k \quad (2.16.2)$$

$$B_{k+1} := \prod(B_k, q_k, w_k) \quad (2.16.7)$$

$$\prod(B, q, w) := B + \frac{qq^T}{q^T w} - \frac{Bw w^T B}{w^T B w} \quad (2.16.8)$$

The above formula yields a positive definite matrix B_{k+1} provided that B_k is positive definite and $q_k^T w_k > 0$.

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

$\dot{\phi}_{P,incr,KD}[n]$	Upshifting Speed at Kickdown dependent on the gear	rpm
$\dot{\phi}_{P,decr,KD}[n]$	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

$\dot{\phi}_{P,adv,incr}[n, \alpha_{E,dk}]$ 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
$\dot{\phi}_{P,adv,decr}[n, \alpha_{E,dk}]$ 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

$\dot{\phi}_{P,adv,incr,KD}[n]$	Upshifting Speed at Kickdown dependent on the gear	rpm
$\dot{\phi}_{P,adv,decr,KD}[n]$	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

$t_{P,upShiftRemain}[n]$	Remaining Time for Upshifting dependent on the gear	s
$t_{P,DownShiftRemain}[n]$	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

$j_{P,act}$	Current Gear	–
$\dot{\phi}_{P,ref,act}$	Speed	rad/s
$\alpha_{P,act}$	Load Signal	–
$S_{P,KD}$	Kickdown Signal	–
$v_{P,act}$	Velocity	m/s
$c_{P,sel}$	Shifting Program Selector	–

2.16.3.2 Data Output

$j_{P,new}$	Desired Gear	–
$\dot{\phi}_{P,upshifting}$	Speed Upshifting	rad/s
$\dot{\phi}_{P,downshifting}$	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

$\dot{\phi}_{H,soll}(v_V, \alpha_{E,dk})$	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)

$\dot{\phi}_{H,soll}(v_V, \alpha_{E,dk})$	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

$L_{H,soll}(\dot{\phi}, \alpha_{E,dk})$ or $L_{H,soll}(v_V, \alpha_{E,dk})$	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

$\alpha_{H,act}$	Load Signal	–
$\dot{\phi}_{H,ref,act}$	Speed	rad/s
i_H	Current Transmission Ratio	–
V_H	Velocity	m/s
M_H	Torque	Nm
$\dot{\phi}_{H,out,control}$	Output Speed	rad/s

2.17.3.2 Data Output

$\dot{i}_{H,dem,act}$	Desired Transmission Ratio	–
$L_{H,dem,act}$	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.

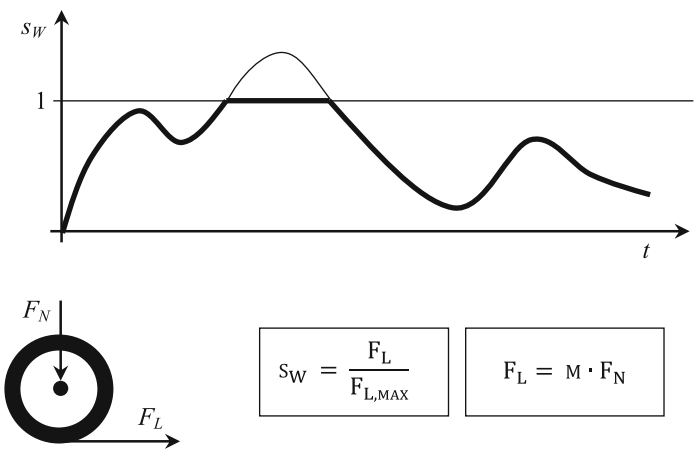


Fig. 2.19 Load transmitting factor [2]

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

$C_{PID,act}$	Actual Value	–
$C_{PID,desired}$	Desired Value	–
$C_{PID,control}$	Control Value	–

2.19.3.2 Data Output

$C_{PID,out}$	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]:

$$\Delta C = C_{PID,desired} - C_{PID,act} \quad (2.19.1)$$

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]:

$$C_{PID,out} = C_{PID,P} \cdot \Delta C + C_{PID,I} \cdot \int_0^t (\Delta C)(\tau) d\tau + C_{PID,D} \cdot \frac{d(\Delta C)}{dt} \quad (2.19.2)$$

In the 2nd mode ('Advanced Signal Control With Limitation'), the entire controller output is calculated by [2]:

$$C_{PID,entireOut} = C_{PID,out} + C_{PID,control} \quad (2.19.3)$$

2.19.4.2 Output Value Limitation

$C_{PID,entireOut}$ is limited by $C_{PID,act,min}$ and $C_{PID,act,max}$.

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	$kg\ m^2$
------------	----------------	-----------

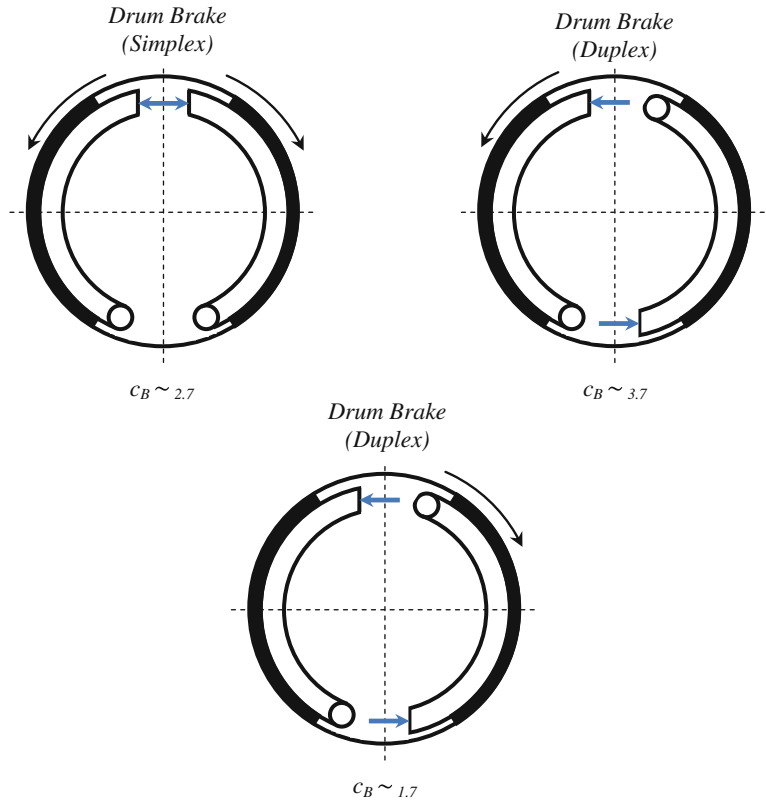


Fig. 2.20 Specific brake factors for different brake types [2]

2.20.3 Input and Output Variables

2.20.3.1 Mechanical Connection

$\dot{\phi}_B$	Angular velocity of the brake	rad/s
$\ddot{\phi}_B$	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

$\dot{\phi}_B$	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]:

$$M_B = 2 \cdot p_B \cdot A_B \cdot \eta_B \cdot \mu_B \cdot r_B \cdot c_B \quad (2.20.1)$$

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

$a_{CO,th}(L_{dk})$	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

$\dot{\phi}_{CO}$	Speed	rad/s
$Z_{CO,cont,in}(i)$	Operation Control 0–4	–
$j_{CO,act}$	Gear Indicator	–
$j_{CO,target}$	Target Gear	–
$\dot{\phi}_{CO,measure_1}$	Measuring Speed 1	rad/s
$\dot{\phi}_{CO,measure_2}$	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

$Z_{CO,acc,out}$	Load Signal	–
$p_{CO,br,out}$	Brake Pressure	bar
$Z_{CO,cl,out}$	Desired Clutch Release	%
$N_{CO,G,out}$	Desired Gear	–
$Z_{CO,sh,up,out}$	Gear Selection Upshifting	–
$Z_{CO,sh,dn,out}$	Gear Selection Downshifting	–
$Z_{CO,sh,sel}$	Control Lever	–
$N_{CO,ret,out}$	Retarder Step	–
$Z_{CO,br,sigl}$	Brake Light Switch	–
$Z_{CO,rev,sig}$	Reverse Gear Switch	–
$\dot{\phi}_{CO,out}$	Speed	rad/s
$v_{CO,out}$	Velocity	m/s
$a_{CO,out}$	Acceleration	m/s ²
$t_{CO,out}$	Real Time	s
$s_{CO,out}$	Distance	m
$Z_{CO,start,out}$	Start Switch	–
$T_{CO,ambient}$	Ambient Temperature	°C
$Z_{CO,cont,out}$	Operation Control	–

(continued)

$Z_{CO,sig,out}(i)$	Course Signal 1–3	–
$Z_{CO,kick,out}$	Kickdown Signal	–
$\dot{\phi}_{CO,measure_1}$	Measuring Speed 1	rad/s
$\dot{\phi}_{CO,measure_2}$	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
--------------	------------------------	----------------

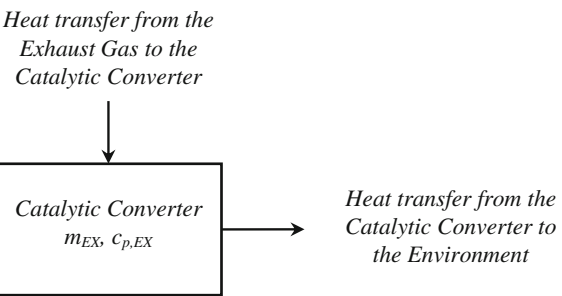
The reference area of the exhaust system is the outside surface area of the catalytic converter. It is needed for the calculation of the heat transfer between the catalytic converter and the ambient air.

$\alpha_{EX,air}$	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

$\eta_{\text{EX,NO}_x}(T_{\text{EX}})$	NO _x —Conversion Efficiency	—
$\eta_{\text{EX,CO}}(T_{\text{EX}})$	CO—Conversion Efficiency	—
$\eta_{\text{EX,HC}}(T_{\text{EX}})$	HC—Conversion Efficiency	—
$\eta_{\text{EX,Soot}}(T_{\text{EX}})$	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

$\alpha_{\text{EX,gas}}(T_{\text{EX}})$	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

$T_{\text{EZ,ext,in}}$	Temperature External	K
------------------------	----------------------	---

2.22.3.2 Data Output

$P_{\text{EX,out}}$	Residual Energy	W
$e_{\text{EX,NO}_x,\text{out}}$	Rest Emissions NO _x	kg/s
$e_{\text{EX,CO},\text{out}}$	Rest Emissions CO	kg/s
$e_{\text{EX,HC},\text{out}}$	Rest Emissions HC	kg/s
$e_{\text{EX,SOOT},\text{out}}$	Rest Emissions SOOT	kg/s
T_{EX}	Temperature	°C

2.22.4 Computation Variables

Q_{EX}	Heat capacity of the exhaust system	J/K
$\eta_{EX, \dots, act}$	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]

$$e_{EX,out} = e_{EX,\dots,in} \cdot (1 - \eta_{EX,\dots,act}) \quad (2.22.1)$$

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 outputs. 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

$X_{ML,out}(i)$	Output 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.

opFU,arith(<i>j</i>)	Arithmetical Operators: +, −, −, /	−
opFU,arith(<i>j</i>)	Operators: Derivation (2 arguments), Integration (3 arguments; the 3rd argument represents the Reset signal, see below)	−
opFU,arith(<i>j</i>)	Operators: Time Derivation (1 argument), Time Integration (2 arguments; the 2rd argument represents the Reset signal, see below)	−
opFU,unary(<i>j</i>)	Operators: abs, sgn, high, low, max, min, 1/x, **, +/-	−
opFU,unary(<i>j</i>)	Operators: rad > deg, deg > rad	−
opFU,trig(<i>j</i>)	Operators: sin, cos, tan, arcsin, arccos, arctan	−
opFU,hyp(<i>j</i>)	Operators: sinh, cosh, tanh, arsinh, arcosh, artanh	−
opFU,log(<i>j</i>)	Operators: ln, exp	−
opFU,logical(<i>j</i>)	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.

ZFU,C-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]):

ZFU,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.

tFU	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[2] 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

$X_{Mon,in}(i)$	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]:

$$F_L = \mu_{Road} \cdot \mu_{W,Tire} \cdot c_S \cdot c_F \cdot F_{W,s} \quad (2.27.1)$$

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].

$$c_F = 1 - \frac{F_{W,act} - F_{W,s,norm}}{F_{W,s,norm}} \cdot c_{W,s,F} \quad (2.27.2)$$

$F_{W,act}$	actual wheel load
-------------	-------------------

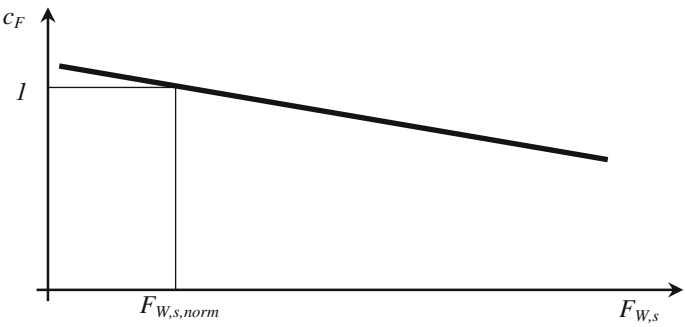


Fig. 2.22 Wheel load correction factor [2]

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	%
-----------------------------	--------------------------	---

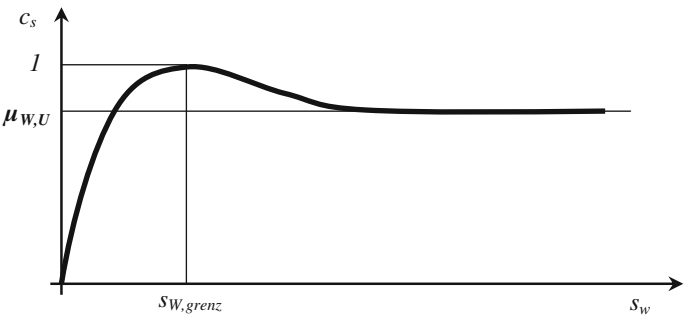


Fig. 2.23 Slip correction factor [2]

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

$\dot{\phi}_{W,in}$	Angular velocity of the wheel	rad/s
$\ddot{\phi}_{W,in}$	Angular acceleration of the wheel	rad/s ²
$\dot{\phi}_{W,out}$	Angular velocity of a virtual wheel	rad/s
$\ddot{\phi}_{W,out}$	Angular acceleration of a virtual wheel	rad/s ²
$M_{W,in}$	Torque on the drive side	Nm
$M_{W,out}$	Vehicle forced moment	Nm

2.27.3.2 Data Input

$T_{W,ambient}$	Ambient Temperature	K
-----------------	---------------------	---

2.27.3.3 Data Output

s_W	Slip Signal	%
$\dot{\phi}_W$	Speed	rad/s
$M_{W,trans}$	Wheel Torque	Nm
$T_{W,act}$	Tire Temperature	K
$F_{W,act}$	Wheel Load	Nm
P_W	Power	W
$P_{W,loss}$	Power Loss	W
$F_{W,roll}$	Rolling Resistance Force	N

2.27.4 Computation Variables

$S_{W,peak,act}$	Actual slip of peak friction point for current road condition	—
$\mu_{W,asym,act}$	Actual Asymptote of slip correction factor for current road condition	—
$C_{W,coeff1}$	Wheel slip coefficient 1	—
$C_{W,coeff2}$	Wheel slip coefficient 2	—
$v_{W,ref}$	Reference Velocity	m/s
$F_{W,a}$	Longitudinal force of tires	N
$F_{W,roll}$	Rolling drag	N
$r_{W,dyn}$	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]:

$$r_{W,dyn} = r_{W,dyn,base} \quad (2.27.4)$$

2. Dynamic wheel radius map ($Z_W = 2$)

The dynamic wheel radius r_W , dy_n is evaluated from the map for the actual wheel speed $\dot{\phi}_{W,out}$ [2].

$$r_{W,dyn} = r_{W,dyn,list}(v_V) \quad (2.27.5)$$

2.27.5.2 Forces and Moments

Rolling Drag Moment [2]

$$M_{W,roll} = F_{W,in} \cdot c_{W,r}(v_{V,act}) \cdot r_{W,dyn} \quad (2.27.6)$$

The rolling resistance coefficient is evaluated out of the map $C_{w,r}(V_v)$ for the actual vehicle velocity.

The rolling resistance is defined as followed [2]:

$$c = c_v + c_\rho c_{RL} + c_T + c_p \quad (2.27.7)$$

c rolling resistance factor

c_v velocity proportional part

$$c_v = c_v(v)$$

c_ρ Rolling resistance influenced by side slip angle [2]:

$$c_\rho = \frac{m_{\text{vehicle}} \cdot v_{\text{vehicle}}^2}{\rho \cdot g} \cdot \text{abs}(\sin(\alpha_{f(r)})) \quad (2.27.8)$$

$a_{f(r)}$ side slip angle

c_{RL} wheel load proportional part [2]:

$$c_{\text{RL}} = c_{\text{RL}}^* \cdot (F_{\text{N}} - F_{\text{N},\text{Norm}}) / F_{\text{N}} \quad (2.27.9)$$

c_{RL}^* reference wheel load proportional part

$F_{\text{N},\text{Norm}}$ reference wheel load

c_{T} temperature proportional part [2]:

$$c_{\text{T}} = c_{\text{T}}(T_{\text{U}}) \quad (2.27.10)$$

c_{p} tire pressure proportional part [2]:

$$c_{\text{p}} = c_{\text{p}}^* \cdot (p_{\text{Norm}} - p_{\text{act}}) / p_{\text{Norm}} \quad (2.27.11)$$

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 ($\mu_{\text{u,road}}$) the Slip Characteristics can be evaluated from the $S_{\text{W,peak}}(\mu_{\text{u,road}})$ and $\mu_{\text{w,asym}}(\mu_{\text{u,road}})$

With this, we calculate the slip coefficients [2]:

$$C_{\text{w,coeff1}} = 2 - \frac{2 \cdot \arcsin(\mu_{\text{w,asym,act}})}{\pi} \quad (2.27.12)$$

$$C_{\text{w,coeff2}} = \frac{1}{S_{\text{W,peak,act}}} \cdot \tan \frac{\pi^2}{4 \cdot (\pi - \arcsin(\mu_{\text{w,asym,act}}))} \quad (2.27.13)$$

Reference Velocity [2]

$$\text{If } v_{\text{V,act}} > \dot{\phi}_{\text{W,in}} \cdot r_{\text{W,dyn}} \rightarrow v_{\text{W,ref}} = v_{\text{V,act}} \quad (2.27.14)$$

$$\text{Else } \rightarrow v_{\text{W,ref}} = \dot{\phi}_{\text{W,in}} \cdot r_{\text{W,dyn}} \quad (2.27.15)$$

Current wheel slip

Independently from the operating mode the wheel slip results from [2]

$$s_W = \frac{\dot{\phi}_{W,in} \cdot r_{W,dyn} - v_{V,act}}{v_{W,ref}} \quad \text{for} \quad |v_{W,ref}| < 10^{-4} s_W = 0 \quad (2.27.16)$$

Slip difference

The slip difference is defined as difference between the actual slip and the infinite slip with the peak friction value [2].

$$\Delta S_W = S_W - S_{W,peak,act} \quad (2.27.17)$$

Selection for different ΔS_W [2]

$$\begin{aligned} \Delta S_W &< 0 \\ M_{W,slip} &= 0 \end{aligned} \quad (2.27.18)$$

$$\begin{aligned} \Delta S_W &\leq 0.03 \\ M_{W,slip} &= -\text{SIGN}(S_W) \cdot 5 \cdot 10^5 \times \Delta S_W^2 \end{aligned} \quad (2.27.19)$$

$$\begin{aligned} \Delta S_W &> 0.03 \\ M_{W,slip} &= -\text{SIGN}(S_W) \cdot 5 \times 10^5 \cdot 0.03 \cdot (2 \cdot \Delta S_W - 0.03) \end{aligned} \quad (2.27.20)$$

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]:

$$\begin{aligned} C_{W,lim} &= \sin C_{W,coeff1} \cdot \arctan(C_{W,coeff2} \cdot S_W) \\ &\cdot \tanh \left[3.6 \cdot \left(v_{V,act}^2 + 0.0278 + (\dot{\phi} \cdot r_{W,dyn})^2 \cdot 0.02 \right) \right] \end{aligned} \quad (2.27.21)$$

$$F_{W,pot} = F_{W,in} \cdot \mu_{W,tire} \cdot \mu_{u,road} \quad (2.27.22)$$

For the actual wheel slip, the maximum transmittable force is [2]:

$$F_{V,a,lim} = C_{W,lim} \cdot F_{W,pot} \quad (2.27.23)$$

The moment of the vehicle (acting at the virtual wheel with $r = 1$ m) is defined as followed [2]:

$$M_{V,virt} = F_{V,a,lim} \cdot 1 \text{ m} \quad (2.27.24)$$

For the actual longitudinal force $F_{W,a}$

For the actual longitudinal force, the necessary slip correction factor can be calculated back [2]:

$$C_{W,act} = \frac{F_{W,a}}{F_{W,pot}} \quad (2.27.25)$$

$$C_{slip} = \frac{F_{W,a}}{F_{W,pot} \cdot C_{w,coeff1} \cdot C_{w,coeff2}} \quad (2.27.26)$$

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]:

$$M_{W,trans} = -(F_{W,a} \cdot r_{W,dyn} - M_{W,roll} - M_{W,lip}) \quad (2.27.27)$$

Wheel power

The wheel power is calculated out of the transmitted wheel torque and the wheel speed [2]:

$$P_{W,trans} = M_{W,trans} \cdot \dot{\phi}_W \quad (2.27.28)$$

2.27.5.3 Rolling Resistance Model

Determination of the exterior diameter and the surface area [2]:

$$D_{W,design} = D_{W,seat} + \frac{2R_W \cdot W_W}{100} \quad (2.27.29)$$

$$A_W = D_{W,design} \cdot \pi \cdot W_W + 2\pi \left(\frac{D_{W,design}^2}{4} - \frac{D_{W,seat}^2}{4} \right) \quad (2.27.30)$$

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]:

$$F_{W,roll} = F_{W,roll,stab} [1 + k_{W,emp} (T_{W,act} - T_{W,stab})] \quad (2.27.31)$$

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]:

$$\begin{aligned}
 F_{W,roll,stab} = & c_{W,roll,ISO} \cdot F_{W,act} \left(\frac{p_{act}}{p_{W,ISO}} \right)^{\alpha_W} \left(\frac{F_{W,act}}{F_{W,ISO}} \right)^{\beta_W} \\
 & \cdot \left[1 + b \left(\frac{v_{W,act} - v_{W,ISO}}{v_{W,ISO}} \right) + c \left(\frac{v_{W,act} - v_{W,ISO}}{v_{W,ISO}} \right)^2 \right] \\
 & \cdot [1 + c_{W,ambient}(T_{W,ISO} - T_U)]
 \end{aligned} \tag{2.27.32}$$

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]:

$$Ra_D = \frac{g \cdot \beta_W (T_{W,act} - T_U) \cdot D_{W,design}^3}{\nu \alpha} \tag{2.27.35}$$

with [2]:

- g gravitational constant (9.81 m/s²)
- β_W volumetric thermal expansion coefficient of air (which can be approximated as $\frac{2}{T_{W,act} + T_U} [K^{-1}]$)
- ν [m/s²] kinematic viscosity of air (evaluated at $\frac{T_{W,act} + T_U}{2}$ through interpolation in a table)

α [m/s²] 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]:

$$Nu_D = 0.15 Ra_D^{0.333} \quad (2.27.36)$$

$$c_{W,heat} = \frac{Nu_D \cdot k_{W,therm}}{D_{W,design}} \quad (2.27.37)$$

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]:

$$T_{W,act}(t) - T_{W,act,last} = \frac{1}{m_W \cdot C_{W,heat,equiv}} \int_0^t [F_{W,roll} \cdot v_{W,act} - c_{W,heat} \cdot A_W (T_{W,act,last} - T_U)] d\tilde{t} \quad (2.27.38)$$

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]:

$$F_{W,roll} = F_{W,roll,stab} [1 + k_{W,emp} (T_{W,act} - T_{W,stab})] \quad (2.27.39)$$

- (5) Concluding the (temperature-independent) aerodynamic drag is added to receive the final, entire **instantaneous rolling resistance** [2]:

$$F_{W,roll} = F_{W,roll} + c_{W,aero} \left(\frac{v_{W,act}}{v_{W,ISO}} \right)^2 \quad (2.27.40)$$

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