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Passenger cars — Simulation model classification —

Part 1:
Vehicle dynamics

Voitures particulières — Classification des modèles de simulation —

Partie 1: Dynamique du véhicule

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components*.

A list of all parts in the ISO 11010 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document has been developed in response to worldwide demand for the standardization of simulation models and their requirements for use in specific applications and driving manoeuvres. During the development and testing of road vehicles questions arise around which simulation models should be applied and how well matched they need to be for performing certain applications with related driving manoeuvres. In the absence of standards it is common practice that experts in different organizations develop their own methods and processes as response to these questions. This causes obstacles when it comes to comparability and model exchange between project partners. Currently, unless the requirements for simulation models undergo extensive elaboration and coordination among the experts involved, there will be major uncertainty with their implementation and quality.

The main purpose of this document is to provide a framework that enables a systematic assignment of certain applications and driving manoeuvres to suitable simulation models and their elements and characteristics. This document classifies the simulation models into certain model classes, their designation number and related elements, characteristics and common modelling method. Assigning models to classes related to specific applications is the responsibility of the user or other regulations and standards. This document contains recommendations in the sense of an appropriate simulation quality in terms of performance tests, thus enabling the user to specify the requirements for the models with reference to this document. This document thus also creates the basis for model recommendations relevant to vehicle dynamics with regard to advanced driver assistance systems and automated driving (ADAS/AD)[19].

Passenger cars — Simulation model classification —

Part 1:
Vehicle dynamics

1   Scope

A systematic framework has been created that facilitates the definition of the requirements of simulation models for certain applications and driving manoeuvres in a standardized manner.

For this purpose, the proposed framework systematically divides the vehicle model into model classes and all model classes into different model types, corresponding to various model characteristics and common modelling methods. The vehicle dynamics manoeuvres have been additionally structured and clustered. Manoeuvres can be assigned to model classes and model types using an allocation and requirements table. This document thus also creates the basis for model recommendations relevant to vehicle dynamics with regard to advanced driver assistance systems and automated driving (ADAS/AD).

The application of the framework and the specification of the model requirements are the responsibility of the user. Alternatively, they may be determined by other regulations and standards. This document contains recommendations for selectable model characteristics in terms of adequate simulation quality with respect to performance tests and associated application patterns. The recommendations can be adapted accordingly to be applied to functional testing.

2   Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3833, *Road vehicles — Types — Terms and definitions*

3   Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3833 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
simulation model
mathematical model for the calculation of the system state variables based on equations describing a vehicle or vehicle sub-system

Note 1 to entry: The vehicle's environment is only modelled as far as required, i.e. friction of the road surface, wind, etc. Models in this context are both, the unit under test (UuT) as well as models to supplement or complete the simulation loop.

3.2
model class
mathematical model based on the vehicle or vehicle sub-systems

3.3
model designation number
gradation of model type and depth with associated model characteristics, represented effects and minimal model inputs and outputs

3.4
steady state model
physical model representing the definitions of steady state equilibrium mentioned in ISO 8855

Note 1 to entry: The model represents the transfer function between model input and output for steady-state equilibrium. The model is not capable of representing the correct time behaviour. Effects caused through small changes in time may be neglected. The model is usually mathematically described by a gain.

3.5
first order model
model, in addition to the *steady state model* (3.4), capable of representing the transient behaviour

Note 1 to entry: The physical model is usually described mathematically by a differential equation with a first order lag force element such as PT1 behaviour with a first order.

3.6
second order model
model defined by a second order force element such as PT2 behaviour with second order

Note 1 to entry: Due to its conjunct complex poles, a time variant input results in an oscillatory output.

3.7
model-in-the-loop
MiL
testing method in which the controller is integrated as a unit under test (UuT) with a *full-function controller* (3.12) into the *simulation model* (3.1) as a controller model

3.8
software-in-the-loop
SiL
testing method whereby the controller is integrated as a UuT with complete controller functionality as application software from the ECU into the *simulation model* (3.1)

Note 1 to entry: See Figure 1.

3.9
processor-in-the-loop
PiL
testing method whereby the controller together with processor emulation is integrated as UuT into the *simulation model* (3.1)

3.10
open-loop control
controller that influences a system's behaviour without a feedback loop, for example based on maps

3.11
principal logic closed-loop controller
controller that influences a system's behaviour with a feedback loop

Note 1 to entry: For principal logic, the controller is implemented in a simplified form, for example, with a PID controller, to demonstrate the control logic.

3.12
full-function controller
controller that is implemented with complete functionality, but with operation restricted to the function control algorithm under test

Note 1 to entry: The controller is realized as either *MiL* (3.7) or *SiL* (3.8).

3.13
ECU-in-the-loop
test method whereby the controller is integrated as a UuT into the *simulation model* (3.1) as a real ECU (Figure 1)

Note 1 to entry: In this document it refers primarily to the controller. The controller is typically implemented in hardware-in-the-loop (HiL).

3.14
full-function virtual ECU
vECU
controller that is implemented as a UuT with the whole ECU software with application and base software (Figure 1)

Note 1 to entry: The controller is realized virtually via emulation in SiL mode. Full-function architecture means software modules such as AUTOSAR connect the virtual ECU to the vehicle's communication network.

3.15
electric brake booster
brake booster that has the ability to amplify the braking force applied by the driver through electrical actuation and autonomously build up pressure without driver actuation

Note 1 to entry: Electric brake boosters consist of a control unit, electric actuator and transmission device [20].

4 Model designation numbers

4.1 General

Each model class may consist of a physical system, including hydraulics and pneumatics, and a controller. This segmentation can be extended to sensor and actuator.

4.2 Physical system

The model of a physical system shall have a model designation number from Table 1, according to the definitions in Clause 3. The force element characteristic ranges from level 0 – no model – to level 3 – second order model and within the sub-designation levels 1.x to 3.x. If a model requires a deeper sub-categorization, the dot notation and a second digit starting from 1 shall be used.

NOTE   The model designation numbers are valid for all vehicle sub-systems from 5.1 except the suspension model, since its designation numbers 1 and 2 lack body masses. Nevertheless, the suspension model designation numbers are adapted reasonably.

Table 1 — Model characteristic and designation number of a physical system

Force element characteristic	Model designation number
None	0
Steady state model	1
First order model	2
Second order model	3

4.3 Controller

The controller model shall have a model designation number from Table 2 according to the definitions in Clause 3. The model characteristics range from level 0 – no model – to level 4 – ECU-in-the-loop (HiL). For level 2 and 3, a deeper subcategorization "3.x" is used.

The subcategorization ".x" of level 2 and 3 defines the range of subsets of the target software (see Figure 1), being included in the test bench. This depends on the scope of investigation, mostly in the context of model-based testing. While level 1 and 2.1 controller models contain a simplified principal logic, level 2.2 models map the target function (MiL) – that is the original control structure function and application. Model level 2.3 (SiL) is based on the compiled target code of the application software (see Figure 1). A level 3.1 model is restricted to the application software (e.g. implementation of control functions and application parameter) as well as the base software such as a virtual ECU (vECU). A level 3.2 model additionally includes the emulation of the processor and the software is compiled for the target processor. Model 4 is the typical HiL as ECU-in-the-loop with hardware-specific software, communication and diagnosis.

Table 2 — Model characteristic and designation number of controllers

Description	Model designation number
None	0
Open-loop control	1
Principal logic closed-loop controller	2.1
Target function: model-in-the-loop (MiL) – application software model only	2.2
Target software: software-in-the-loop (SiL) – application software only	2.3
Target software: full-function virtual ECU (vECU) – application + base software	3.1
Target software: processor-in-the-loop (PiL)	3.2
Target ECU: ECU-in-the-loop (HiL)	4

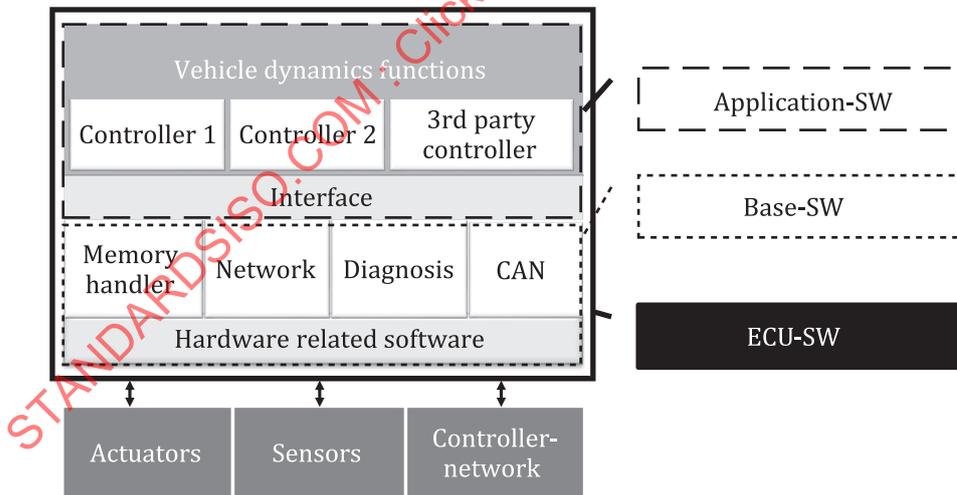**Figure 1 — Subsets of a controller**

Figure 1 illustrates a typical software architecture of a real or virtual control unit in reference to Table 2 with the levels: application software, base software and interfaces to actuators, sensors and network.

NOTE   The performance of a closed-loop controller can be significantly influenced by the time latency of sensor signals.

Compared to the model designation number of the physical system (see 4.2), the designation number of the controller is not mainly influenced by the driving manoeuvre, but by the scope of the investigation. In predevelopment stage, a simple principal logic might be sufficient to evaluate the overall vehicle behaviour; for functional development and safeguarding, the original function should be used. Some exemplary types of investigation concerning the choice of the controller designation number are given in Table 3.

Table 3 — Examples for the selection of controller designation number

Type of investigation	Controller designation number
Preliminary design physical system	0/1/2.1
Functional development (preliminary design)	2.2/2.3
Homologation	2.3/3.1/4
Safeguarding of software implementation	2.3/3.1
Safeguarding of function including operation system	3.1/3.2/4
Systematic functional safeguarding in spite of a lack of a virtual controller model	4

5   Model classes

5.1   General

The vehicle model is structured in the following model classes according to Figure 2: vehicle / body (VH), powertrain (PT), brake (BR), steering (ST), suspension (SU), aerodynamics (AE) and tyre (TY) and the road with road surface (RS) and road wind (RA). Some model classes consist only of a physical system XXM, others as combination of a physical system XXM and a control system XXC. The models refer to common vehicle systems as currently used in passenger cars. The user can create model prototypes of future systems accordingly.

Independently of the above-mentioned structure of the models, a controller is not necessarily mapped to a single ECU. An ECU will likely host more than one single controller. In addition, a controller algorithm might be distributed over multiple ECU. This is of importance especially for higher model designation numbers, where base software or other properties of the ECUs shall be considered.

NOTE   It is possible that there are differing allocations and interfaces defined in Clause 5. In this document, the axial rotation of wheels is calculated in the powertrain (PTM) and is passed to the tyre (TYM) and brake (BRM).
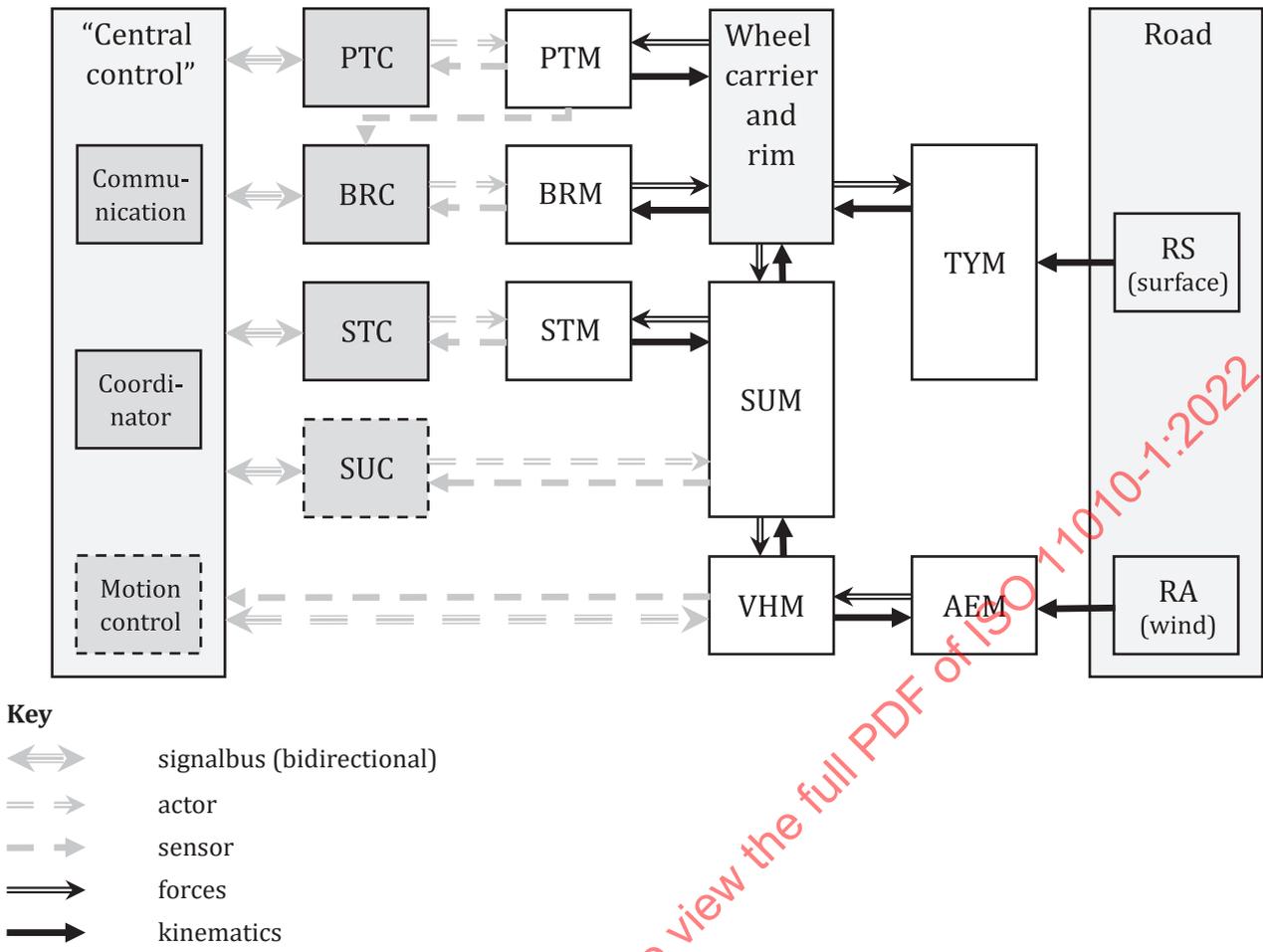
Key

⇔	signalbus (bidirectional)
= →	actor
− ➤	sensor
⟹	forces
➤	kinematics

Figure 2 — Top-level model architecture

The control systems XXC are specific for their components XXM. Sometimes a "central controller" coordinates the component-specific controller. For ADAS a sensor-based environment detection and trajectory planning is necessary as well as a trajectory control. Trajectory control generates target values for the component-specific controllers: in longitudinal direction for the powertrain (PTC) and brake (BRC) and in the lateral direction for the steering (STC). Due to the fact that the "central controller" is very specific to the manufacturer it is not classified in this document.

NOTE   The "central controller" can be partitioned into separate control unit(s) or added to the control unit of the specific controller(s).

The capital letters in parenthesis are the model classes' abbreviations. The selected designation number of a model class shall be written in the following syntax:

<ModelClass>M<MechanicalSystemDesignationNumber >

<ModelClass>C<ControllerDesignationNumber>

The actual names and numbers shall replace the placeholders in angled brackets. For the <ModelClass> the specified abbreviation shall be used. The syntax resembles that in the following examples:

STM2

PTM2 PTC4

BRM2.1 BRC3.1

NOTE   This can be extended to sensor and actuator via the syntax:

<ModelClass>S<SensorDesignationNumber>

<ModelClass>A<ActuatorDesignationNumber>

5.2 Vehicle/body

The model class vehicle (VH), with the architecture in Figure 3, is actually targeted to describe the modelling of the vehicle body. However, depending on the designation number, it is possible that the vehicle body is not isolated from the whole vehicle model. The higher the designation number, the better the vehicle body can be isolated.

The model class vehicle (VH) shall have a designation number of the physical system (VHM) in accordance with Table 4.

The designation numbers for class vehicle does not follow exactly the classification as described in Table 1. Here the principle "best practice" applies. Thus, the models are clustered into three groups:

VHM1: one body model;

VHM2: multi-body model split sprung mass, unsprung mass, rigid bodies and look-up table for suspension;

VHM3: multi-body model split sprung mass, unsprung mass, multi-body suspension.

In the group VHM1 the tyre is combined with the vehicle, while in the groups VHM2 and VHM3, the vehicle body can be isolated from suspension and tyre. As an example, the widely used single-track model belongs to VHM1, and VHM3 has the 3D-vehicle body model with local stiffness/stiffness matrix within its scope.
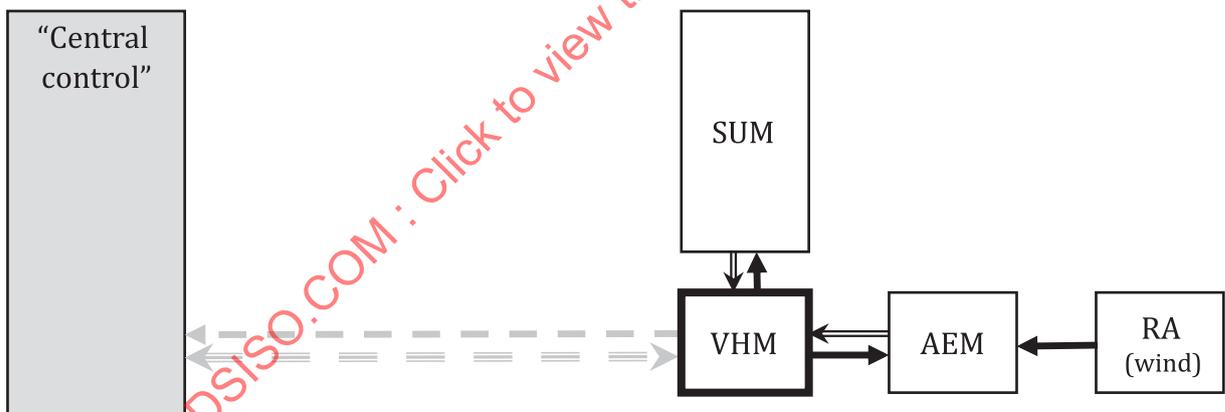

Figure 3 — Vehicle architecture

Table 4 — Vehicle system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
VHM0	None					
VHM1.1	Single mass 1-DoF	Single mass, one dimensional	Starting, braking	(ODE) differential equation (1-DoF)	Forces (braking, accelerating)	ax
VHM1.2	Single track model	Lateral dynamics model with constant velocity	Understeer/oversteer	(ODE) differential equation / function test for controller	Steering angle	ay, yaw
VHM1.3	Single track model with lateral load transfer	VHM1.2+ lateral load transfer due to ay, load dependent tyre model required	Load transfer due to vehicle lateral acceleration tyre characteristics	VHM1.2+ load dependent tyre forces due to roll	VHM1.2	VHM1.2, roll
VHM1.4	Single track model with longitudinal dynamics	VHM1.2+ longitudinal load transfer due to ax, load dependent tyre model required	Load transfer due to vehicle longitudinal acceleration tyre characteristics	VHM1.2+ load dependent tyre forces due to pitch/ function test with controller (e.g. ACC)	VHM1.1+ VHM1.2	VHM1.1+ VHM1.2
VHM2.1	3D-model with rigid bodies and look-up table suspension	3D-model with rigid bodies including wheel bounce	MBD mechanics (split sprung mass, unsprung masses)	3D-model with suspension + tyres/ function and performance test of controller	Forces moments / aero	Motion of bodies and hard points
VHM3.1	3D-model with rigid bodies and MBD suspension	3D-model with rigid bodies including wheel bounce	MBD mechanics (split sprung mass, unsprung masses)	3D-model with suspension + tyres/ function and performance test of controller	Forces moments / aero	Motion of bodies and hard points
VHM3.2	3D-model with flexible elements (global stiffnesses)	VHM3.1. and global stiffnesses (torsional stiffness, bending)	VHM3.1	VHM3.1+ global stiffnesses lumped in concentrated spring-damper elements	VHM3.1	VHM3.1
VHM3.3	3D-model with flex bodies (local stiffnesses)	VHM3.2 + local stiffnesses	VHM3.2 + local deformation	VHM3.2 + parts flexible modelled or full flex-body (stiffness matrix)	VHM3.2	VHM3.2

5.3 Aerodynamics

The model class aerodynamics (AE), with the architecture in Figure 4, shall have a model designation number of the physical system (AEM) in accordance with Table 5. The modelling of aerodynamic effects is divided into three subgroups. Aerodynamic effects in the vehicle models discussed in this document are modelled by forces and sometimes by moments. The first effect considered is in general the drag force, see AEM1.1. The next level includes vertical forces described by the sublevel AEM1.2. Sublevel AEM1.3 is included in order to take sidewind effects into account in the model.
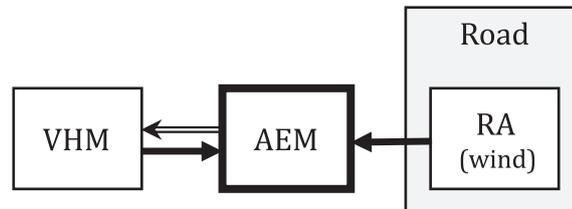

Figure 4 — Aerodynamics architecture

Table 5 — Aerodynamics system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
AEM0	No aerodynamics					
AEM1.1	Drag	Only longitudinal drag forces are considered.	Drag-forces	Force from constant factor or curve	Vehicle velocity	Long force
AEM1.2	AEM1.1 + vertical	Additionally, front and rear lift forces are considered.	Vertical forces which influence limit under-/oversteer balance.	Force from constant factor or curve	Vehicle velocity	Long and vertical forces, pitch moment
AEM1.3	AEM1.2 + sidewind	All three dimensions are considered.	Sidewind sensitivity	Forces and moments (or a pair of forces) from constant factor or fields	Vehicle and air velocity	AEM1.2 + yaw, roll moment

5.4 Brake

The model class brake (BR) with the architecture in Figure 5 contains the brake controller (BRC) and the physical system (BRM) is specified as hydraulic service-brake system. The hydraulic service-brake system allows the driver to reduce speed or to stop the vehicle completely. Therefore, the driver activates the braking effect by pressing on the brake pedal. A vacuum booster amplifies the force. It is transmitted to the wheel brake cylinders via the tandem master brake cylinder to two independent hydraulic circuits.

For active systems like ABS, TCS or ESC, a hydraulic unit is attached between master brake cylinder and brake pipes. This hydraulic unit contains valves and a pump, either for modulating the wheel cylinder pressure, or to actively build up the pressure for stabilizing the vehicle. A related algorithm, also responsible for the brake force distribution between front and rear axles, controls the valves and pump.

Nowadays electric brake boosters are becoming more commonplace, either as a substitute for vacuum boosters in electrical vehicles, or with combined usage in hybrid and electrical vehicle as well as for autonomous pressure build-up for advanced driver assistance systems functions (ADAS). Alternatively, electric brake booster [20] and ESC-unit can be combined in an aggregated solution.

The model class brake (BR) with the architecture shown in Figure 5 shall have a model designation number of the physical system (BRM) in accordance with Table 6 and a designation number of the controller (BRC) in accordance with Table 7.

The model class brake (BR) contains the mechanical and hydraulic part (BRM) as well as the related controller (BRC). BRM1.0 is a pure algebraic calculation of the pressure in the wheel brake cylinder. BRM2.1 calculates the pressure of the wheel brake cylinder in dependency of the master cylinder pressure as an input. Depending on elasticities in the pipes and wheel brake cylinder, a volume flow is calculated and integrated as a final pressure in the wheel brake cylinder. BRM2.2 is based on the same principle, considering the flow through valves based on pre-calculated characteristic maps or polynomial and the volume flow induced by the pump. In addition, BRM3.1 considers pressure oscillations in the brake pipes and wheel brake cylinders up to about 40 Hz, whereas BRM3.2 includes the dynamics of pump and valve bodies. Booster functions are considered purely algebraically in BRM3.3 and in BRM3.4 with a feedback control function (oscillatory) using pedal position, pedal force or requested deceleration as input. The ESC and electric brake booster controller (BRC) are available as MiL-, SiL-, PiL- and HiL-versions. The interface between the controller of the electric brake booster and ESC is specified[20].

The BRM-block is linked by kinematic and kinetic quantities to the PTM-block. The BRC-block is linked to the vehicle controller network by a bus-system (CAN, FlexRay). VHM- and PTM-block provide some sensor signals to the BRC-block hardwired. Blocks BRC and BRM exchange actuation and sensor feedback signals.

NOTE   It is possible that there are differing allocations and interfaces. In this document, the axial rotation of wheels is calculated in the powertrain (PTM) and is passed to the tyre (TYM) and brake (BRM).
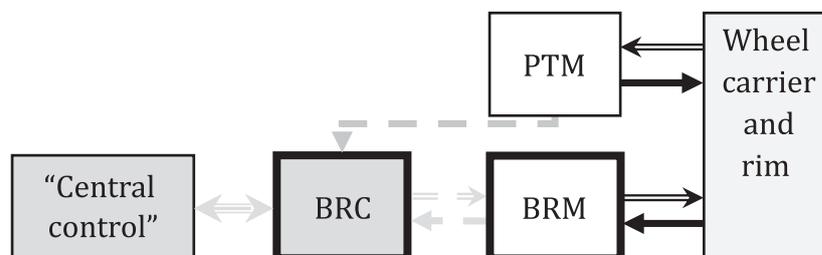

Figure 5 — Brake architecture

Table 6 — Brake system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
BRM0	No brake pressure modulation					
BRM1	Steady-state behaviour	Pressure in wheel brake cylinder, system oriented	Pressure in wheel brake cylinder proportional to master cylinder pressure	Pressure in wheel brake cylinder as a function of target deceleration, vehicle mass, tyre radius, brake friction coefficient	For example, target deceleration	Pressure in wheel brake cylinders
BRM2.1	First order behaviour without control	Pressure in wheel brake cylinder, system oriented	Volume flow and pressure due to elasticity in the brake system	Bernoulli-characteristic curves and lines, (Typ1), pV-characteristics; <10 DGLs 1. Ord.	Pressure in the master brake cylinder	Pressure in wheel brake cylinders
BRM2.2	First order behaviour with control	Pressure in wheel brake cylinder, system oriented	BRM2.1 with valve and pump actuation	BRM2.1 with valve current and pump voltage >10 DGLs 1. Ord., 1 DGL 2. Ord.	Pressure in the master brake cylinder, valve and pump actuation	Pressure in wheel brake cylinders, voltage of pump motor
BRM2.3	First order behaviour ESC with algebraic electric brake booster function	Pressure in wheel brake cylinder, system oriented	BRM2.2 with algebraic Booster function	BRM2.2, actuation of motor and motion of the booster- and valve bodies	Brake pedal force, or actuation of booster motor, actuation of valves and pump	Booster-travel, pressure in wheel brake cylinders voltage of pump motor
BRM3.1	Second order behaviour without control	Pressure in wheel brake cylinder, system oriented	BRM2.x with brake pipe dynamics up to 40 Hz	BRM2.x with brake pipe dynamics based on acoustic theory	Pressure in the master brake cylinder, valve and pump actuation	Pressure in wheel brake cylinders, voltage of pump motor
BRM3.2	Second order behaviour with control	Pressure in wheel brake cylinder, component oriented	BRM3.1 with dynamics of valve and pump body	Characteristic curves and lines, (Type 2), Newton- Euler-Eq.	Pressure in the master brake cylinder, valve and pump actuation	Pressure in wheel brake cylinders voltage of pump motor
BRM3.3	Second order behaviour ESC with oscillatory electric brake booster function	Pressure in wheel brake cylinder, system oriented	BRM3.2 with dynamic booster function	BRM3.2 actuation of motor and motion of the booster- and valve bodies	Brake pedal force, or actuation of booster motor, actuation of valves and pump	Booster-travel, pressure in wheel brake cylinders voltage of pump motor

Table 7 — Brake controller

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
BRC0	No regulation, no control					
BRC1	Open-loop control					
BRC2.1	Principle logic	Stabilisation of wheel rotation and/or yaw rate of vehicle body	Control based on idealized and complete signals	ABS-, FZR-PID-controller	Vehicle-, wheel velocities, steering angle, yaw rate, pressure in the master cylinder	Brake torque at wheels
BRC2.2	Full function MiL	ESP-function	Model of ECU-ASW-code of the controller, signal conditioning, observers	MiL: ABS, TCS, yaw control-function modelled	Wheel speed signals, steering angle, yaw rate, pressure in the master cylinder, reduced set of BUS signals	Actuation of valves and pump, interventions into powertrain management
BRC2.3	Full function SiL	ESP function	ECU-ASW-code of the controller, signal conditioning, observers	SiL: ABS, TCS, yaw control 1:1-code compiled for WINx	Wheel speed signals, yaw rate, lateral acceleration, steering angle, pressure at master cylinder, reduced set of BUS signals	Actuation of valves and pump, interventions into power-train management, controller network
BRC3.1	Full function SiL	ECU-code (no real time capability)	ECU-ASW and BSW-code	SiL: complete code of ECU-SW (CSW) compiled for WINx	Wheel speed signals, yaw rate, lateral acceleration, steering angle, pressure at master cylinder, CAN/FlexRay	Actuation of valves and pump, interventions into power-train management, controller network
BRC3.2	Full function PiL	Emulated ECU (in control network of ECU(s) or static restbus)	Performance concerning processor	PiL: complete code of ECU-SW (CSW) on emulated target-ECU	Wheel speed signals, yaw rate, lateral acceleration, steering angle, pressure at master cylinder, CAN/FlexRay	Actuation of valves and pump, interventions into power-train management, controller network
BRC4	Full function HiL	ECU-code (real time capability)	Real ECU	HiL: complete code of ECU-SW (CSW) on target-ECU	Wheel speed signals, yaw rate, lateral acceleration, steering angle, pressure at master cylinder, CAN/FlexRay	Actuation of valves and pump, interventions into power-train management, controller network

5.5 Powertrain

The model class powertrain (PT) with the architecture in Figure 6 contains the powertrain controller (PTC) and the physical system (PTM). The PTM mostly consists of a motor, a gear box and an axle gear box. Additional further components might be included to perform torque splitting (e.g. transfer case, differential lock) or electrical support (hybrid drive). The PTC consists principally of a motor control unit and a gear control unit; additional control units might have a share in torque splitting depending on the physical system PTM.

The PTC evaluates the engine target torque and the gear as a result of accelerator pedal and gear lever. In case of (A)DAS or stability control, additional motor torque requests have to be included. The PTM represents the physical system from actors to wheel speeds. The wheel speeds are transferred to the tyre and break model (TYM, BRM) for slip/force calculation.
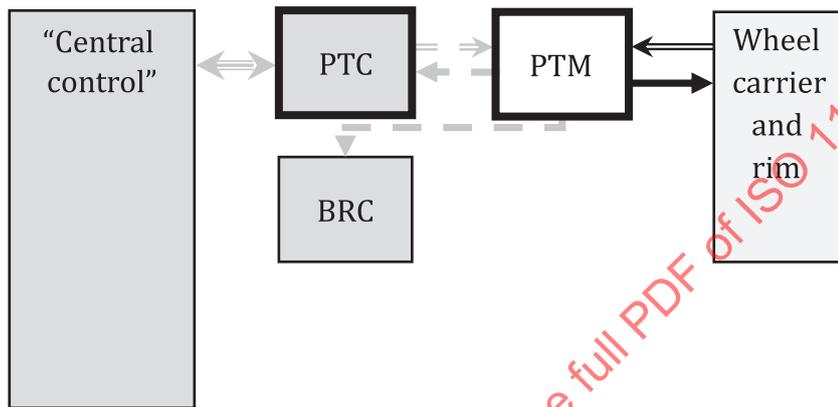

Figure 6 — Powertrain architecture

Various model detailing and the associated designation numbers are presented in Table 8 and Table 9.

The model PTM1 is an exception, due to the fact that it does not need a PTC and TYM. It describes directly the correlation between accelerator pedal and driving force. The model designation number PTM2 is a transient model with rigid components, PTM3 is an oscillatory model with an elastic powertrain.

NOTE 1   Since there is an innumerable number of combinations concerning torque splitting and electric components, 5.5 restricts itself to a generic interface. Nevertheless, it is essential to consider all torque splitting components in order to obtain valid results in driving dynamics. In this case the modelling method is similar to the controller defined in Table 9. The torque distribution can be given as boundary condition (open loop) or can be calculated by a controller (-> PTC) and friction model (-> PTM) in the case of a clutch.

NOTE 2   In case of torque split components (e.g. transfer case, differential lock) the torque distribution can be given as boundary condition or can be calculated by an (inverse) model using constraints, if the torque split is realized by a clutch.

Table 8 — Powertrain system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
PTM0	None	The superordinate model does not need the velocity as a state or uses a constant velocity as boundary condition.				
PTM1	Steady state behaviour	Static correlation accelerator pedal to sum of driving forces	Motor torque full load/ drag; gear ratio (maybe reduced); AT: torque converter	Look up table	Accelerator pedal	Sum of driving forces(longitudinal)/torque
PTM2	First order behaviour	Model includes all driving torque generator (combustion/electric) and converter and the calculation of wheel speeds.	PTM1 + inertia (may be reduced) motor dynamics; efficiency factors/power loss	Motor transfer function(s); fixed torque distribution; rigid drive components; idealized shifting operation; efficiency factors.	Engine target torque (PTC); gear (PTC); brake (BRM) and tyre reaction torques (TYM)	Wheel speeds; engine speed
PTM3	Second order behaviour	Formula PTM2 but with elastic powertrain	PTM2 + Non-steady motor torque; powertrain stiffness and inertia and friction/damping	MKS important: adequate suspension and tyre model has to be used.	Formula PTM2	Formula PTM2

Table 9 — Powertrain controller

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
PTC0	No control					
PTC1	Open-loop control	Realization of torque request by the driver (accelerator and brake pedal and the gear lever)	Realization of torque request, AT: gear shifting program	Look up tables	Accelerator pedal, gear lever, engine speed (ptm).	Engine target torque, gear
PTC2.1	Closed-loop control	Principal logic / PID	PTC1 + requests motor torque from, e.g. stability control, (A) DAS …	Transfer functions	PTC1 + requests motor torque, e.g. (A) DAS	Formula PTC1
PTC2.2	Target function	Full-function logic	Test of target function	MiL	Input signals	Output signals
PTC2.3	Target-application software	Original software restricted to application software only	Validation of software	SiL	Input signals	Output signals
PTC3.1	Target-ECU software	Original ECU software (application and basis software)	Validation of software	SiL	Input bus messages	Output bus messages
PTC3.2	Target-ECU software	Emulated ECU (in control network of ECU(s) or) static restbus	Performance concerning processor	PiL	Input bus messages	Output bus messages
PTC4	Target ECU	Hardware ECU in control network of ECU(s) or static restbus	Hardware ECU test	HiL	Input bus messages	Output bus messages

5.6 Steering

The model class steering (ST), as mechanical coupled steering system, with the architecture in Figure 7 shall have a model designation number of the physical system (STM) in accordance with Table 10 and a model designation number of the controller (STC) in accordance with Table 11. The STC evaluates a required torque/force as a result of the external input, e.g. the steering wheel angle and torque, velocity and acceleration, the vehicle velocity and the torsion bar torque. In case of stability control and ADAS/AD, additional torque/angle requests have to be included. The STM represents the physical system from steering wheel to the steering rack or steering arm at the steering knuckle (tie rods and bearing in the wheel carrier are excluded). The rack or steering arm forces or positions are transferred to the SUM +, e.g. via ball joints.
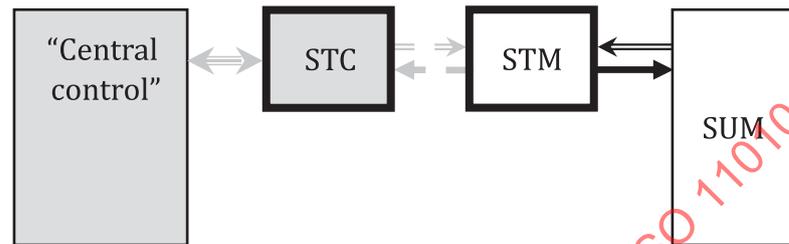
Figure 7 — Steering architecture

Table 10 — Steering system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
STM0	No model	Fixed wheel position or steering angle input				
STM1.1	Steady-state behaviour	Function between steering wheel angle and steering angle	Steering ratio without compliance	Factor or lookup table for steering ratio	Steering wheel angle	Rack position
STM1.2	Steady-state behaviour with boost function	Function between steering wheel angle and steering angle and steering torque (Boost curve)	Steering ratio without compliance and steering assistance	Factor or lookup table for steering and torque ratio	Steering wheel angle / steering wheel torque	Rack position
STM2.1	First order behaviour	Elasto-kinematic steering function between steering wheel angle and steering angle	Steering ratio and compliance	With factor or lookup table and a stiffness element	Steering wheel angle/ steering wheel torque	Rack position
STM2.2	First order behaviour with steering torque	Elasto-kinematic steering function between steering wheel angle and steering angle and steering torque	Steering ratio with elasticity under force impact and steering torque	With factor or lookup table for steering ratio, compliance and steering wheel torque	Steering wheel angle / steering wheel torque	Rack position
STM3.1	Second order behaviour	Elasto-kinematics steering model includes steering ratio, elasticity, mass, inertia, damping and coulomb friction.	Actual steering angle, steering forces and rack position due to elasticity, mass, inertia, damping and friction	2 to 4 DOF with elasticity, mass, inertia, damping and spring friction element	Steering wheel angle / steering wheel torque	Rack position
STM3.2	Second order behaviour with friction elements	Model includes additional friction element.	Stick slip effect and hysteresis	2 to 4 DOF with elasticity, mass, inertia, damping and spring friction	Steering wheel angle / steering wheel torque	Actuator position
STM3.3	Second order behaviour with detail components	Detailed with column, rack and torsion bar behaviour	Stick slip effect and hysteresis detailed for column, rack, torsion bar and power assistance	2 to 4 DOF with elasticities, masses, inertias, damping and spring frictions of column and rack. Torsion bar with elasticity and spring friction Power assist as look-up table	Steering wheel angle / steering wheel torque	Actuator position
STM3.4	Second order behaviour with detail components and assist unit	Column, rack, torsion bar and assist unit behaviour	Stick slip effect and hysteresis detailed for column, rack, torsion bar and power assistance	5 and more DOF with spring friction modelling	Steering wheel angle / steering wheel torque	Actuator position

Table 11 — Steering controller

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
STC0	No control					
STC1.1	Open loop control	Map based open loop control	Steering assistance	Lookup table power assist	Torsion bar torque/angle	Assist torque/force/ current
STC1.2	Open loop advanced control	Map based open loop control with multiple maps	Steering assistance	Power assist + other functions, e.g. damping/ active return	Vehicle velocity, torsion bar torque/angle, steering wheel angle/angle velocity/angle acceleration	Assist torque/force/ current
STC2.1	Principal logic/ PID control	Simplified controller the basic controller functions	Steering assistance	Function model with simple PID control	Vehicle velocity, torsion bar torque/angle, steering wheel angle/angle velocity/angle acceleration	Assist torque/force/ current
STC2.2	Full function MiL	Controller model with full-function logic	Steering assistance, function behaviour, energy consumption, functional safety	Controller functions are detailed modelled	Vehicle velocity, torsion bar torque/angle, steering wheel angle/angle velocity/angle acceleration	Assist torque/force/ current
STC2.3	Full function SiL	Full-function logic with generated code	Steering assistance, function behaviour, energy consumption, functional safety	SiL only functions (e.g. *.dll) based on generated code	STC2.2 + Restbus simulation	Assist torque/force/ current
STC3.1	Full function SiL	Control network of driving ECUs	Steering assistance, function behaviour, energy consumption, functional safety	SiL with virtual ECU including bus communication	STC2.2 + Restbus simulation	Assist torque/force/ current
STC3.2	Full function PiL	Emulated ECU (in control network of ECU(s) or) static restbus	Performance concerning processor	PiL	Input bus messages	Output bus messages
STC4	Full function HiL	Hardware ECU in control network of ECU(s) or static restbus	Hardware ECU test	HiL	Input bus messages	Output bus messages

5.7 Suspension

The model class suspension (SU) with the architecture in Figure 8 shall have a model designation number of the physical system (SUM) in accordance with Table 12. The suspension is the bridging part between the tyre and the vehicle body. In general, the steering system is attached to the suspension to allow steering, by rotating the wheel and respectively the tyre.

The models can be grouped into two classes in addition to the 'None' suspension designation. The first group contains empirical models with K&C and force elements. The simplest one SUM1.1, allows only longitudinal movement. For manoeuvres like start and stop, this might already be sufficient.

SUM1.2 allows vertical movement of each wheel in addition to the DoF from SUM1.1. Bounce, roll and pitch movements are possible. Only if steering is defined the vehicle could follow a defined path. This would also require a more complex tyre model with lateral stiffness.

In SUM2.1 the wheel and the tyre change their orientation. Especially toe and camber change because of kinematics and compliance. The dependency of toe and camber, bounce/rebound and lateral forces and moments, and rack displacement is stored in tables, i.e. they are pre-calculated. This allows very fast calculation in comparison to SUM3.1.

The suspension in SUM3.1 is not described by pre-calculated curves like in SUM2.1 but through a complete multi-body-dynamics system, which means by rigid parts, joint-force-elements, like springs and dampers, and non-linear rubber elements. Especially during design phase, these models are used for detailed analysis. In addition, SUM3.1 can be the base for SUM2.1. SUM3.1 can be used to calculate kinematics and elasto-kinematics, also named compliance.

SUM3.2 uses the modelling method from SUM3.1, where some or all parts can be modelled flexibly. In most industry applications the finite elements method (FEM) could be used, but also other approaches like Euler beams could be used.
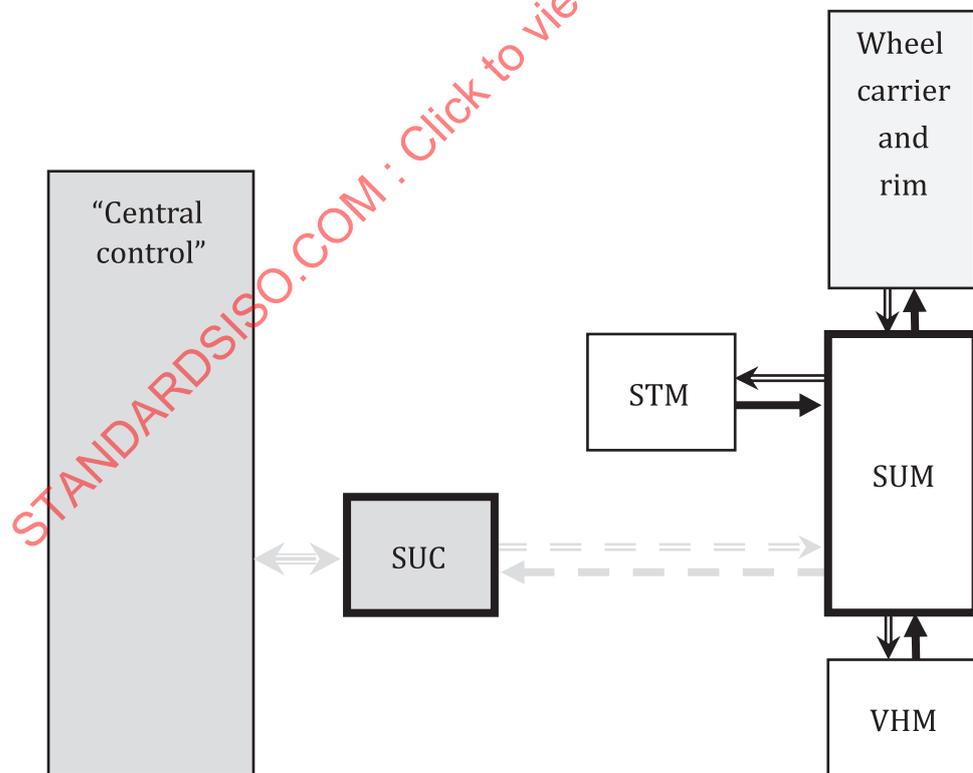

Figure 8 — Suspension architecture

Table 12 — Suspension system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
SUM0	None					
SUM1.1	Rolling, longitudinal dof	Single constraint to allow rolling or straight-line movement	Start and brake	Constraint equation	-	Velocity
SUM1.2	SUM1.1 + bounce/rebound	SUM1.1 and bounce and roll	roll and pitch possible	SUM1.1 and spring damper element	Vertical force	Displacement (bounce, rebound)
SUM2.1	SUM1.2 + kinematic and compliance	Kinematic and compliance are stored in table	Toe, camber, wheel centre position dependent on bounce	SUM1.2 + kinematic and compliance either measured or calculated from SUM3.1 (3.2) model	Rack-displacement, wheel travel, forces and moments	Toe, camber, wheel centre position
SUM3.1	Multi-body-dynamics system	Suspension model as MBD (rigid bodies, joints, force elements, including non-linear rubber elements)		DAEs	Rack-displacement, wheel travel, forces and moments	Toe, camber, wheel centre position
SUM3.2	SUM3.1 + flexible bodies	SUM3.1 + flexible bodies/structures		DAEs	Rack-displacement, wheel travel, forces and moments	Toe, camber, wheel centre position

Table 13 — Suspension system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
SUC0	No control	Passive springs, passive damper, passive anti-roll-bar (ARB)				Spring force, damper resistance, ARB torque, current
SUC1.1	Open-loop control	Feedforward control, driving mode set by customer	Comfort feel	Look-up table	Suspension displacement (roll angle ...), driving mode	Spring force, damper resistance, ARB torque, current
SUC1.2	Advanced open-loop control	Driving mode defined by situation ("terrain detection"), adaptive algorithm	Comfort feel	Look-up table + detected driving mode	Suspension displacement (roll angle ...), driving mode	Spring force, damper resistance, ARB torque, current
SUC2.1	Principal logic closed-loop control	Control based on target value and feedback information	Comfort feel	Look-up table + detected driving mode +deviation to target value	Suspension displacement (roll angle ...), driving mode, deviation to target value	Spring force, damper resistance, ARB torque, current
SUC2.2	Full function MiL	Controller as model in source code + component model (suspension) + vehicle model	Comfort feel, functional behaviour, functional safety, energy consumption	MiL	As above + functional safety/ energy consumption relevant information	Spring force, damper resistance, ARB torque, current, checksum
SUC2.3	Full function SiL	As above, but controller as compiled model (*.dll)	Comfort feel, functional behaviour, functional safety, energy consumption	SiL only functions (e.g. *.dll)	As above	Spring force, damper resistance, ARB torque, current, checksum
SUC3.1	Full function SiL	As above, but controller as compiled model (*.dll) + ECU emulation	As above + bus behaviour + virtual ECU properties	SiL with virtual ECU, rest-bus simulation, fixed point values, computational time, low-level signal check	As above + rest-bus	Spring force, damper resistance, ARB torque, current, checksum
SUC3.2	Full function PiL	Emulated ECU (in control network of ECU(s) or) static restbus	Performance concerning processor	PiL	Input bus messages	Spring force, damper resistance, ARB torque, current, checksum
SUC4	Full function HiL	As above, but software running on ECU hardware	As above + bus behaviour + real ECU properties (hardware)	HiL with real ECU	As above + rest-bus	Spring force, damper resistance, ARB torque, current, checksum

5.8 Tyre

The model class tyre (TY) with the architecture in Figure 9 shall have a model designation number of the physical system (TYM) in accordance with Table 14. The model class TIC is not described, since there are no controllers for the tyre that do not belong to any other of the described model classes. The model receives the wheel rotation from the powertrain model and the triaxial position and speed as well as the wheel angles from the suspension model. By using this information and the road inclinations angles, the tyre forces and moments can be calculated and transmitted to the powertrain and suspension model.
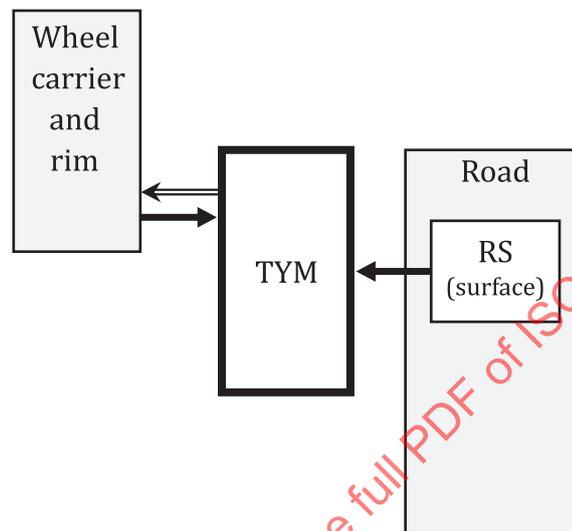
Figure 9 — Tyre architecture

The model class tyre is used to calculate the tyre forces and moments for a specific use case. In case of very simple longitudinal dynamics a TYM1.1 can be sufficient, whereby the maximum tyre force is calculated merely by evaluating the coulomb friction equation. For simple lateral dynamics TYM1.3 is used to calculate the tyre forces by assuming a constant cornering stiffness with a maximum value for the force. TYM1.4 shall be used in order to combine simple longitudinal and lateral dynamics. This model class takes into account the mutual dependency of lateral and longitudinal tyre forces.

The model class TYM2.x describes a simulation with a transient tyre behaviour. In contrast to TYM1.x, where the time dependent behaviour is neglected, this model class takes into account simple time-dependent dynamics. If the consideration of Bohr torques is necessary, the TYM2.2 shall be used.

Model class TYM3.x describes full oscillatory behaviour of the tyre. TYM3.1 is particularly designated for accelerator pedal step input simulations and therefore, combines longitudinal dynamics and simple vertical dynamics of the tyre. TYM3.2 takes into account all rigid body modes of the tyre belt, which may reach up to 80 Hz. TYM3.3 shall use an enhanced calculation for the belt motion, which includes flexible belt modes with frequencies up to 200 Hz. In this case the belt is usually represented by a FEM or MKS type model. If a misuse load case is simulated, a tyre of model class TYM3.4 should be used. This model class considers the forces occurring when the tyre belt touches the rim.

Table 14 — Tyre system

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
TYM0	No tyre					
TYM1.1	Steady-state behaviour tyre model for maximum tyre forces	Calculation of tyre force using friction coefficient and tyre contact force	Maximum of transferrable force	Formula	Friction coefficient and tyre contact force	Maximum of transferrable force
TYM1.2	Steady-state behaviour tyre model for calculation of lateral forces	Calculation of tyre force using friction coefficient, slip angle and tyre contact force	Constant cornering stiffness with maximum	Formula/table	Slip angle, friction coefficient and tyre contact force	Lateral tyre force
TYM1.3	Steady-state behaviour tyre model	Model for combined longitudinal and lateral dynamics	Traction circle, nonlinear cornering stiffness, force dependence of wheel position	Formula/table	Slip angle, camber angle, friction coefficient, longitudinal slip and tyre contact force	Lateral and longitudinal tyre force
TYM2.1	First order behaviour tyre model	All forces and moments are calculated with PT1 behaviour.	Traction circle, nonlinear cornering stiffness, force dependence of wheel position, PT1 behaviour	Formula/table/differential equation	Complete tyre data set (longitudinal and lateral), wheel position (x,y,z,α,β) and wheel motion (derivative of wheel position vector), rotational speed	Longitudinal force, lateral force, contact force, tyre self-aligning torque, camber torque
TYM2.2	First order behaviour tyre model with drilling torque	TYM2.1 + drilling torques	Traction circle, nonlinear cornering stiffness, force dependence of wheel position, PT1 behaviour, drilling torque	Formula/table/differential equation	Complete tyre data set (longitudinal and lateral), wheel position (x,y,z,α,β) and wheel motion (derivative of wheel position vector), rotational speed	Longitudinal force, lateral force, contact force, tyre self-aligning torque, camber torque
TYM3.1	Tyre model for accelerator pedal step input	Combined calculation of vertical and longitudinal dynamics	Vertical stiffness, longitudinal force as a function of longitudinal slip, contact force and friction coefficient	Formula/table/differential equation	Position of wheel centre (z), longitudinal slip	Longitudinal force, contact force
TYM3.2	Second order behaviour tire model (rigid ring)	Consideration of belt-tipping, translation and torsion	All rigid ring modes up to 80 Hz	Differential equation of the belt	Complete tyre data set (longitudinal and lateral), wheel position (x,y,z,α,β) and wheel motion (derivative of wheel position vector), rotational speed	Longitudinal force, lateral force, contact force (for rim and road), tyre self-aligning torque, camber torque
TYM3.3	Second order behaviour tire model (flexible ring)	TYM3.1 + flexible tyre belt	All tyre belt modes up to 200 Hz	FEM/MKS	Complete tyre data set (longitudinal and lateral), wheel position (x,y,z,α,β) and wheel motion (derivative of wheel position vector), rotational speed	Longitudinal force, lateral force, contact force (for rim and road), tyre self-aligning torque, camber torque

Table 14 *(continued)*

Model type	Model description	Description	Effects	Common modelling methods / typical application area	Minimal model input	Minimal model output
TYM3.4	Second order behaviour tyre model with consideration of rim-belt-contact	TYM3.2 + consideration of rim-belt-contact	All tyre belt modes up to 200 Hz, including rim-belt-contact	FEM/MKS	Complete tyre data set (longitudinal and lateral), wheel position (x,y,z,α,β) and wheel motion (derivative of wheel position vector), rotational speed	Longitudinal force, lateral force, contact force (for rim and road), tyre self-aligning torque, camber torque

5.9   Road surface

The model class road surface (RS) shall have a model designation number of the physical system (RSM) in accordance with Table 15.