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Transmission drivability evaluation on HiL-bench and dummy TCU

Masterthesis

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Abstract

The main purpose of the master thesis is to compare transmission drivability evaluations of real vehicle tests and drivability evaluations of simulation runs in different virtual environments.

System simulation with dummy controls is the first virtual environment, which has been considered. These simulations are typically performed on very early stages of a transmission development, where a new transmission architecture is analyzed to understand its shifting behavior, identify possible drivability issues, and outline a rough control strategy. The comparison with real measurement will allow understanding the limits of these relatively simple models in predicting drivability in a concept phase where no prototype hardware is available.

Hardware in the loop (HiL) simulation is performed using the real control unit and real application software, coupled with a system plant model of higher level of detail. This kind of simulation is typically performed in parallel to test bench or vehicle development with prototype hardware. The comparison with real measurement will allow understanding the correlation between HiL tests drivability and real vehicle behavior and identify which calibration-related activities can be effectively performed in a HiL environment.

The drivability evaluation is done with AVL Drive. AVL Drive is a software tool, which gives us an objective representation of drivability. Real vehicle tests are done on the AVL test track in Gratkorn with an online measurement of AVL Drive rating, whilst with dummy TCU and HiL the simulation is done offline first and later with given results from AVL Drive.

The ideal goal would be to get same drivability rating for any kind of measurement. But this is nearly impossible to achieve, so the goal of this thesis is to simulate the vehicle on HiL and dummy TCU, evaluate the results and try to figure out what is causing the drivability rating deviations and how these issues can be fixed.

Abbreviations and formula symbols

HiL……………………… Hardware in the loop

MiL……………………… Model in the loop

DCT…………………… Dual Clutch Transmission

AT………………………. Automatic transmission

CVT……………………. Continuously variable transmission

MT……………………. Manual transmission

AMT…………………. automated manual transmission

DHT…………………. dedicated hybrid transmission

SST……………………. single speed transmission

MBD…………………. Model-Based Design

DMU…………………. DRIVE Main Unit

DR……………………. DRIVE Rating

ICE…………………… Internal Combustion Engine

TCU…………………. Transmission Control Unit

AT-9………………… 9-speed Automatic Transmission

SW………………….. Software

POUS……………… Power-on upshift

PFDS…………………Power-down downshift

I/O…………………… Inputs/Outputs

US_PO_D ………. Upshift Power-on Drive mode

DS_TI_D_P ……. Downshift Tip in Drive-Mode positive Torque

DS_TI_D_N ……. Downshift Tip in Drive-Mode negative Torque

DS_CO_D ………. Downshift Coast/Brake on Drive-Mode

US_TO_D_Q Upshift Tip-out Drive-Mode Quick

US_TO_D_S Upshift Tip-out Drive-Mode Slow

Table of content

1. Introduction

During transmission design and transmission software development our biggest goal is to make the Transmission as compact as possible and providing the best possible drivability, by doing this it is also necessary to take in consideration that the transmission should give the best possible fuel consumption, it's not too heavy and the costs are not exceeding the budget. This master thesis is focusing on evaluating the possible drivability even before entering the car. This can be done either on the HiL with the same TCU as it is used later in the car or on MiL with a dummy TCU. Biggest advantage on evaluating the drivability on HiL or even before on MiL is cost reduction, it is much easier and much faster to simulate all maneuvers necessary for evaluating the drivability with a computer. Main issue on doing this is to apply all car characteristics into a virtual environment. Because this is a big topic, exceeding this master thesis, I am focusing on just one part of the drivability evaluation and this is gearshift and changing the components accordingly to make the behavior comparable with the application in a car as good as possible.

Gearshift DR evaluation is done with 4 different kind of gearshifts. Power on Upshift and Power down/Coast Downshift are the two most common ones, the other two are Power on Downshift and Power down/Coast Upshift. For every kind of gearshift there is at least one testcase provided, to evaluate DR of gearshifts.

The simulated vehicle used for all measurements is a 9-speed automatic transmission car model. AT-9 is during the master thesis an ongoing project and the evaluation of the drivability can be compared during the project. Therefore, the DR on HiL may change from release to release, because SW changes constantly and every change may affect also the DR. This is not a problem for the dummy TCU, because there the SW changes, which are done specifically for a vehicle, do not affect the dummy TCU and so, after adjustments, the DR for one vehicle is always the same. The main problem in an ongoing project is that not all test cases have been driven and the ones driven are not exactly like it is described in the AVL DRIVE catalogue. So it might happen that DR from AVL DRIVE catalogue may be a bit different, but in general the DR should match between testcases from catalogue and the ones driven with the vehicle.

In general, AVL DR evaluation is important during SW development. The Human aspects on what is good and what is bad drivability is very subjective, therefore we have AVL DRIVE, which is giving us an objective perspective on how good our drivability is. Of course, AVL DRVIE is still a SW tool and has its challenges to evaluate drivability perfectly, but with enough input data, as for example, acceleration, torque engine speed changes during gearshift the problems and errors of DR evaluation are getting smaller and DR gets as objective as its possible. With AVL DRIVE we get how good our drivability is, but the downside of it is, that is only giving us one value for drivability and not giving any ideas how and where to improve our model if DR is bad. So, in the end we get the information if we are on a good way to provide a good product, but finding out the problems to improve the DR is still in the hands of an engineer to find and solve them by themselves.

During my master thesis the main goal was to bring the DR of the Plant model driven with the HiL and dummy TCU as near as possible to the DR given by vehicle measurements. In the beginning it was important to bring the data from vehicle measurements in a form so that the same data can be used in virtual environment. On the HiL it meant to create a python script to read this data accordingly and with dummy TCU it was enough to have an excel sheet with all the data. When the simulation is ready to run with the same data set as the vehicle it's important to have the velocity profile matched, because different velocity profiles cause different gearshift times which can lead to major differences in DR evaluation. Having matching velocity profile with the right dataset does not mean that the DR is automatically matched, for this to happen, there have to be made some model adjustments for acceleration, torque and engine speed as this are the main contributor for correct DR.

2. Tested vehicle

Measurements and simulations have been done on AT-9 SUV vehicle. Vehicle parameters can be a reason for different DR evaluation. A vehicle with same characteristics and different resistance may have different DR, because of the behavior of the car on the road, same goes with smaller tires or heavier car for example. So, when comparing DR of two different vehicles it is important to also consider the characteristics which can lead to DR differences. For my master thesis this should not be a problem, because all data is the same for virtual tests and real vehicle tests.

2.1. Vehicle specifications

Table 1 Vehicle [1]

Gas tank volume	80 l
Total length	4856 mm
Wheelbase	2850 mm
Curb weight	2250 kg
Gross weight	2950 kg
Frontal area	2.96 m^2
Drag coefficient	0.347
Wheel radius	0.377 mm

Table 2 Resistance coefficient [1]

A0	289.92 N
B0	0.96 N/kph
C0	0.059 N/(kph^2)

2.2. Engine

The engine is a 4-cylinder 2.0 l gasoline motor.

Table 3 Engine properties [1]

Engine displacement	2.0 l
Number of cylinders	4
Idle speed	750 1/min
Maximum speed	5800 1/min
Fuel heating value	44000 kJ/kg
Fuel density	747 kg/m^3

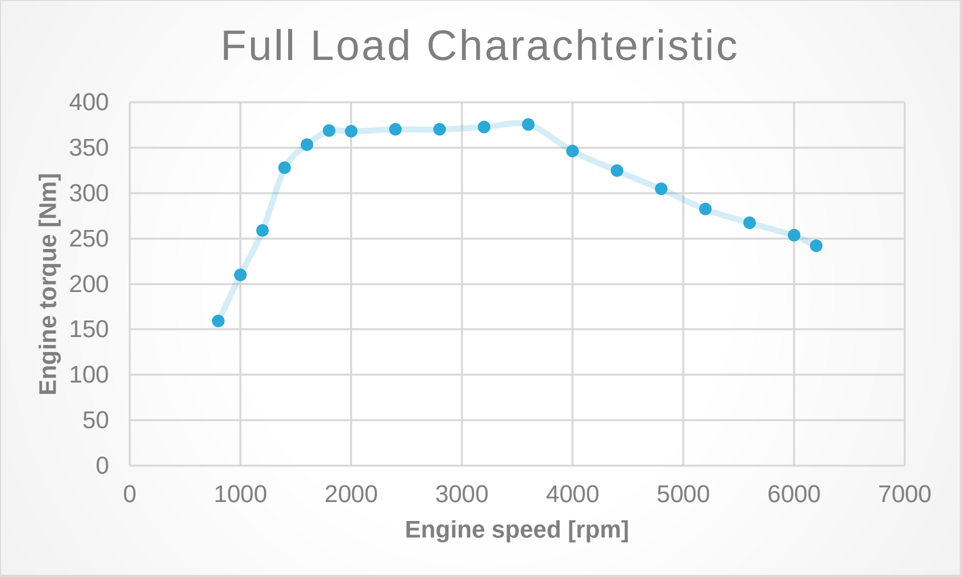


Figure 1 Engine full load characteristic [1]

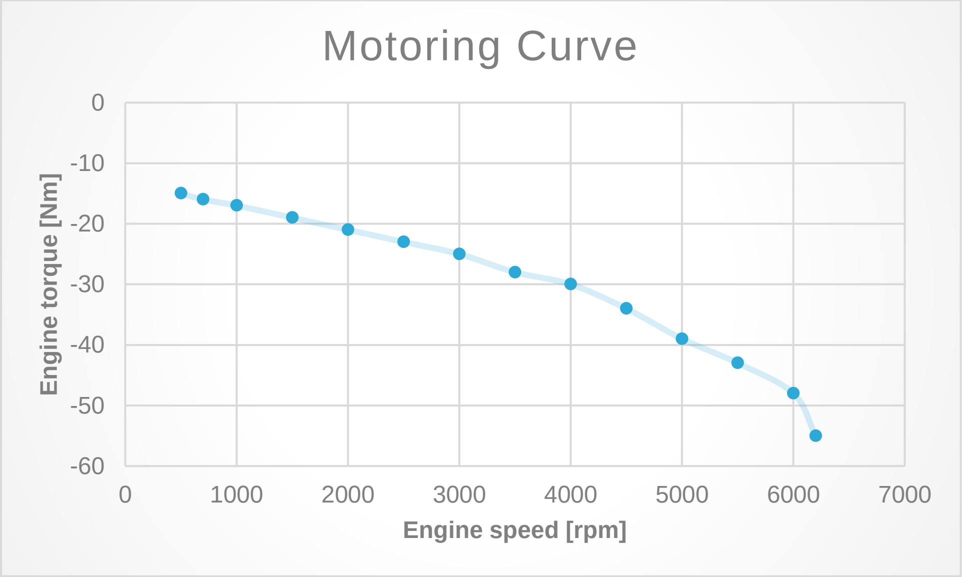


Figure 2 Motoring curve [1]

2.2.1. Automatic transmission AT

ATs provide full power shift functionality so that the driver does not need to change gear ratios or actuate a launch device manually; all of this is handled by the transmission and its control. Shifting elements of ATs are designed based on frictional power transfer, so torque handover between different ratios can be done without interrupting the power flow to the output shaft. One of the major criteria for transmission development and calibration is the shift quality and acceleration in which I will look more into detail for my thesis, other criteria as fuel consumption, noise, durability are also important but will not be considered during my thesis.

During launch and low speed driving, a torque converter is applied in almost all ATs to deliver high comfort.

Mostly, a combination of planetary gear sets is used to provide the different gear ratios of an AT. They offer a high power density for the transmission's power transfer from torque converter to the transmissions output shaft, but limit the freedom designing and adjusting the individual ratios. As planetary gear sets provide more than one ratio and power split capabilities, shifting elements are used to guide the torque flow and power flow through the transmission.

Recently also dog-clutches have been introduced in automatic transmissions for even more compact installation space in front-transverse applications (with the ZF 9-speed automatic transmission being the first-ever use of interlocking dog clutches in a passenger car powershift transmission). [2]

There are three kind of shifts in ATs, a direct shift, direct skip shift and indirect shift. A direct shift is a shift between two neighbor gears, by having just one applying shift element and one releasing element. A direct skip shift is like a direct shift, just that here the direct neighbor gear is skipped. Indirect shifts are utilizing more than two shift elements, so for them more effort in software and calibration is used. [3]

Some alternative transmissions to evaluate DR could be dual clutch transmissions (DCT), manual transmission (MT) or continuously variable transmission (CVT). DR evaluation for these transmissions is the same, just the components causing DR are different. For DCT the main components are the 2 clutches and rails, compering this to AT there are some new components in rails, which have to be modeled correctly to shift the forks in the right direction so that gears can be engaged and this can cause some additional problems in DR evaluation if model is not good. [4]. MT on the other hand are build up much easier and does not have so many components, but the drivability is much more Driver depended then on AT. CVTs cover much smaller market the ATs and MTs but their benefit of operating the ICE in best operation mode deliver the possibility for lower fuel consumptions and emissions. In case of drivability CVTs have a big advantage compered to others, because they make it possible to drive gearless, so all the influences during gearshifts, which are causing the DR to get lower are here nonexistent and have the potential for best drivability. [5]

2.2.1.1. AT-9 transmission

AT-9 is together with AVL developing its own 9 gear automatic transmission, with 5 planetary gearsets and as shifting elements two brakes and 4 clutches are used.

Table 4 AT-9 Planetary gearset ratios

Planetary gearset	Ratio
1	97/47
2	100/44
3	83/37
4	86/34
5	26/10

Table 5 AT-9 Transmission ratios

Gear	Transmission ratio
1	5.29
2	3.24
3	2.25
4	1.64
5	1.21
6	1
7	0.87
8	0.72
9	0.60

Figure 3 Shows the transmission architecture. With this schematic and with the help of the Shift matrix from Table 6, the torque flow for each gear can be seen. In the transmission architecture each number is one shaft of the transmission and the additional letter to the number is the connection to planetary gearset. C1 to C4 and B1, B2 are the clutches and GS1 to GS4 all the planetary gearsets. For drivability the most important parts are all the clutches. The clutches give the most to drivability, because they are the

main part during a gearshift, so proper clutch management and modeling is important. When clutch is modeled fine, the transition between one gear to another goes smoothly without any unexpected torque or acceleration behavior and the DR can be high. Examples of direct shits in this transmission in table 6 are all neighboring shifts, for from 1st to 2nd gear C2 is off going and C1 is incoming, so for high DR this part should go fast and smooth, because as long as C1 is not open, C2 cannot be closed and if this takes too long it will cause lower DR. An direct skip shifts in this AT are shifts from 4th to 1st gear or from 3rd to 5th gear, where the gears are not neighbors, but to come from one gear to another just one clutch has to be closed and one opened. An indirect shift is then from 6th to 3rd this kind of shifts happen when there is a sudden acceleration and there is a need for higher torque, so the gear changes quickly from 6 to 3.

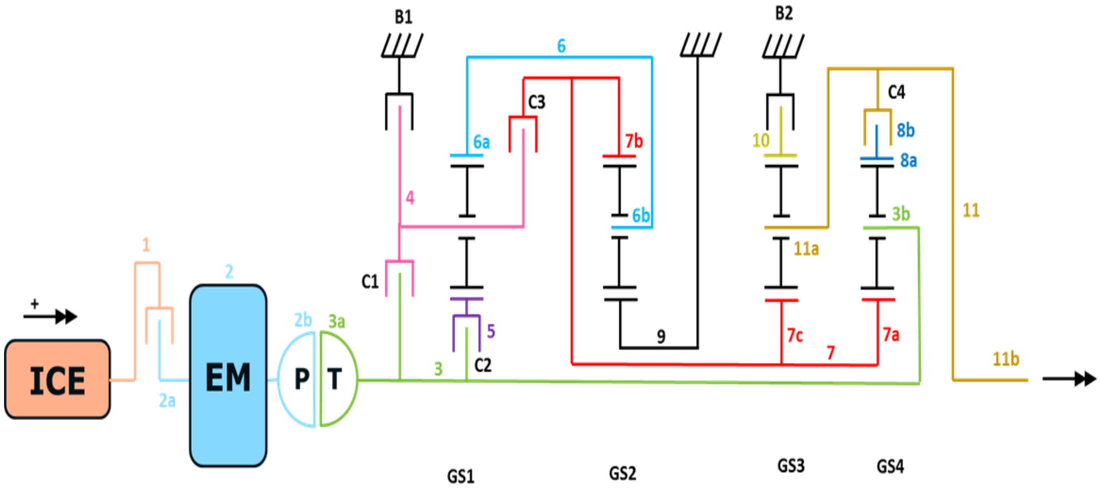


Figure 3 AT-9 transmission architecture

Table 6 Shift Matrix

Shift Matrix						
C1	C2	C3	C4	B1	B2	
						N
	x	x			x	***1***
x		x			x	***2***
x	x				x	***3***
	x		x		x	***4***
x	x		x			***5***
x		x	x			***6***
	x	x	x			***7***
		x	x	x		***8***
	x		x	x		***9***
	x			x	x	***R***

3. Applied software and hardware

3.1. Transmission Software

The transmission SW is one of the biggest parts in providing good drivability. The process of transmission software with AT-9 project was separated in 3 phases. The A sample where the beginning of the SW development is done, and first tests are driven. B sample where in the end the software has to be nearly finished and ready for the road and last release phase in which the SW has to be ready for serial production of the transmission. During this master thesis all simulations were done with A sample SW, because the project was still on the beginning and Vehicle tests were driven just with A sample SW, therefore DR estimations are not as good as they would have been with a SW from the end of B phase.

For drivability its important from transmission side good clutch and torque converter management. Having good torque converter strategy is important especially in low velocity when Lock-up clutch is opened, and the vehicle is powered by torque converter. For higher gears the torque converter is not important anymore. Clutch management is important always during gearshift, when clutches need to open and close and the difference in drivability between good and bad clutch management is enormous, bad clutch management can lead to unexpected behavior of acceleration and engine speed, which can be detected even by the least experienced driver. So, transmission SW is regarding drivability giving a big influence on drive away, gearshift, acceleration and engine speed.

The whole SW for the AT-9 project is being built with MATLAB/Simulink [6] and is used as a generated code inside the TCU. This TCU is then later used on HiL for HiL simulations. The dummy TCU has a bit different approach. There is no actual TCU in which a SW code is saved, but the whole TCU is one big MATLAB/Simulink subsystem which is connected to plant model I/O for the purpose of various simulations. I/O for both are the same, main inputs are all clutch slip speeds, wheel speed, torque converter and driver request torque, road gradient, pedal positions and gear lever position. Outputs from the transmission are clutch torques, status of the transmission, actual and target gear status and shift status.

Figure 4 shows the main buildup of the dummy TCU during gearshift, which is divided in six parts that happen during gearshift. The first two parts just initializations for shifts. The third phase preparation is the phase where the torque on the off going clutch is slowly decreasing and torque of oncoming clutch is brought to bite torque level. Torque phase is the phase where the torque of the off going clutch is going down to bite point torque and toque from oncoming clutch is increasing to drivetrain torque, this phase ends when both clutch torques are on defined levels. Speed phase is bringing with help of torque intervention on engine or clutch side down when upshift or up when downshift. When speed phase is done, the only remaining phase is reinst, where engine torque is put back to start point and oncoming clutch to where the off going clutch started.

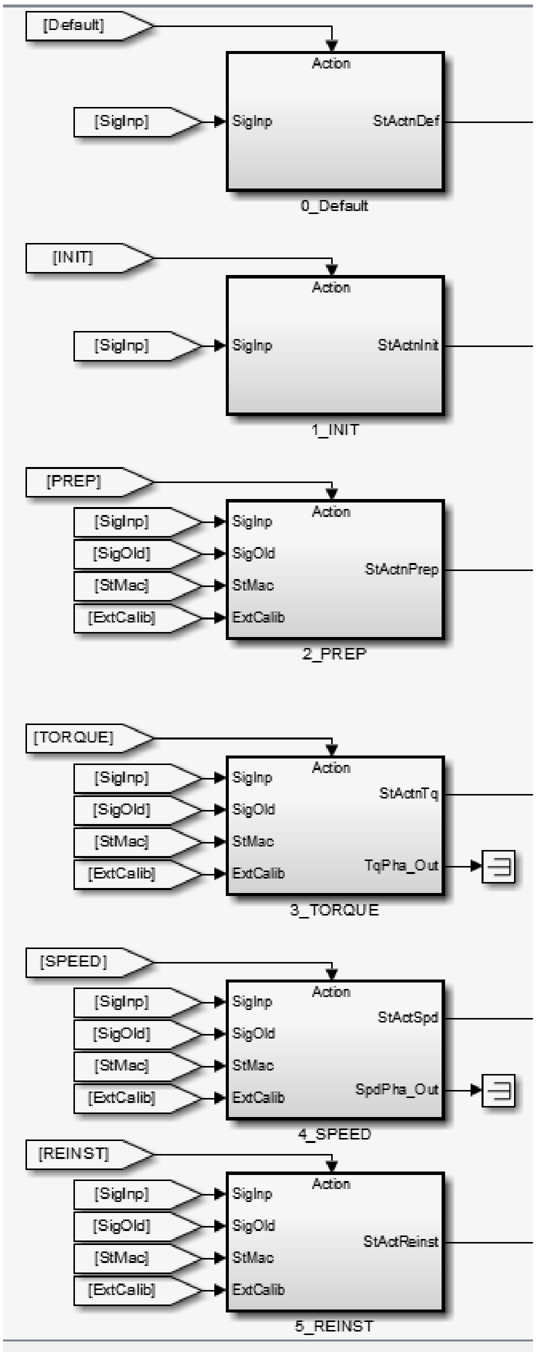


Figure 4 dummy TCU model

3.2. Hardware in the Loop

3.2.1. What is HiL

Hardware-in-the-loop (HiL) simulation is a type of real-time simulation. The control software is deployed to final control unit hardware while the physical behavior of the controlled system and feedback sensors are simulated. A HiL test system replaces the vehicle with a real-time simulation comprising hardware and software that interacts with real I/O as though the physical systems were present, tricking the controller into thinking it is in the assembled product.

Test and design iteration take place as though the real-world system is being used. You can easily run through thousands of possible scenarios to properly exercise your controller without the cost and time associated with actual physical tests.

HiL is mainly used to test your controller design, another use for the HiL is to determine if the physical plant model is valid. [7] [8]

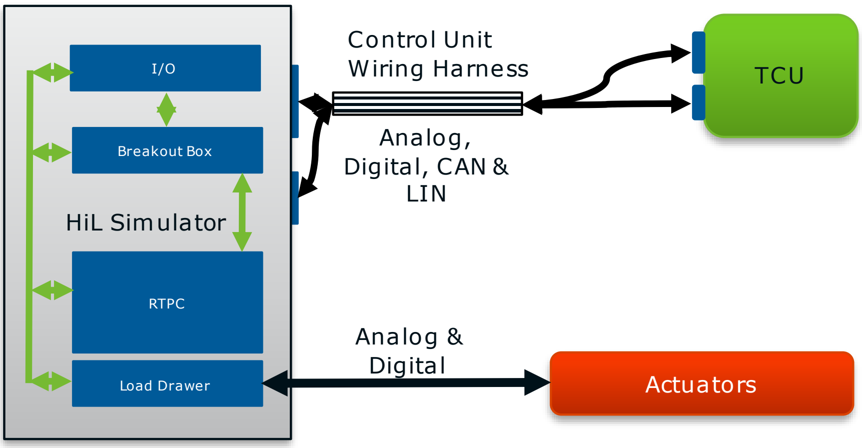


Figure 5 Schematic representation of a HiL system

The setup for the HiL used for this master thesis is described in chapter 3.7.

3.2.2. Why perform HiL simulation

HiL simulation can be used to test the controller design when performing Model-Based Design (MBD). Validation involves using actual plant hardware to test the controller in real-life situations or in environmental proxies (for example, a pressure chamber). In HiL simulation, real hardware for the physical system (plant) must be used. The model is not relying on a naturalistic or environmental test setup. By using the model to represent the plant, HiL simulations offer benefits in cost and practicality.

In this way, HiL simulations are offering cost saving opportunities over validation testing on several areas. HiL simulations tend to be less expensive for design changes. On the MBD workflow HiL simulations can be performed for earlier the validation, so the possible problems can be redesigned and identified early in the project. Finding problems early includes benefits like:

- The team is more likely to improve changes
- Design changes are less costly to implement

Regarding scheduling, HiL simulation offers the possibility to set it up and to run on its own, which is less expensive and more practical than hardware-based validation.

HiL simulation allows monitoring a greater number of physical quantities (e.g. clutch pressures, shaft torque values, etc.) compared to a real vehicle, which requires costly instrumentation. Together with the higher level of repeatability (same maneuver can be re-run without external environmental disturbances), HiL simulation gives the developers higher chances to debug software issues or perform sensitivity analysis on many calibration parameters.

HiL simulation is more practical for testing the controller's response to unusual events then hardware-based validation. For example, on HiL simulations extreme driving conditions such as high speed and extreme braking can be applied, which could otherwise expose test driver to risks especially in early prototype phases. Furthermore, testing of controller reaction in case of mechanical or electrical hardware malfunctions can be easily realized by manipulating plant models. [7] [8]

3.2.3. Limits of HiL simulation

The limits of HiL simulation are driven by the quality of underlying simulation models. On one hand, the requirement of real-time capability of models limits the complexity of physical behavior, which can be represented by the plant model: some effects need to be necessarily simplified to enable real-time execution. On the other hand, some features of the system might be difficult to model or very hard to parameterize without extensive testing campaign for the characterization of the real hardware. ETC, ETC.

3.3.AVL DRIVE

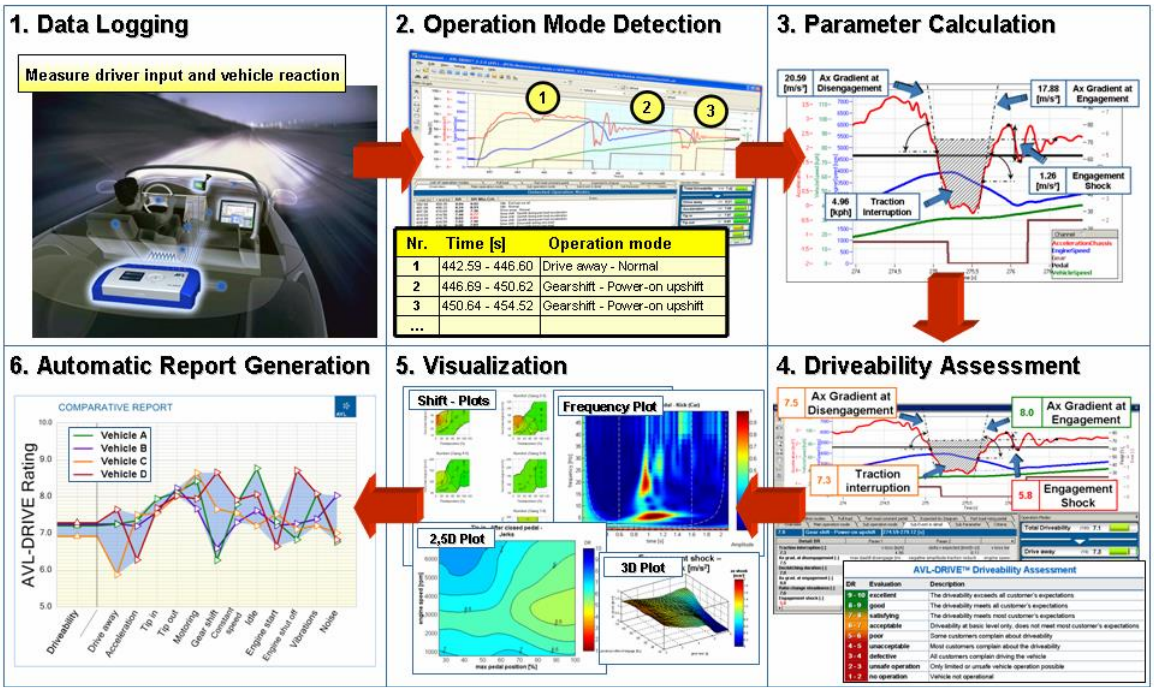
AVL-DRIVE is a tool designed by AVL for the objective real-time assessment and quality control of drivability based on the driver’s perception. For the objective assessment of the highly subjective perception of the driver, procedures have been elaborated to define the evaluation method and formulas. Experiences acquired from internal and external vehicle benchmarks and drivability development projects are continually incorporated in the AVL-DRIVE software. AVL-DRIVE measurements can be done on various vehicle types (e.g. passenger car, bus, motorcycle, truck, tractor) and the following transmission types:

- AMT (automated manual transmission)
- AT (automatic transmission)
- CVT (continuously variable transmission)
- DCT (double clutch transmission)
- DHT (dedicated hybrid transmission)
- MT (manual transmission)
- SST (single speed transmission)

The system needs for normal operation various drivability-related sensors and CAN bus signals, such as longitudinal acceleration, engine speed, vehicle speed, pedal positions and vibrations. These input quantities are collected by the DMU and then passed on to the AVL-DRIVE software for further processing and analysis.

About 100 different driving modes (e.g. part load acceleration, tip-in at deceleration, downshift after kick down) are detected automatically and up to 475 drivability-related criteria (e.g. kick, surge, engine speed fluctuation, response delay ...) are rated in real-time. The automatic classification of driving modes facilitates a fast and comprehensive vehicle analysis. The analysis is done with several criteria kicks, shocks, jerks, shift duration, acceleration during shift etc. All of these criteria have their own DR, so AVL DRIVE gives us exactly which criteria is causing a problem and where should further development look more into.

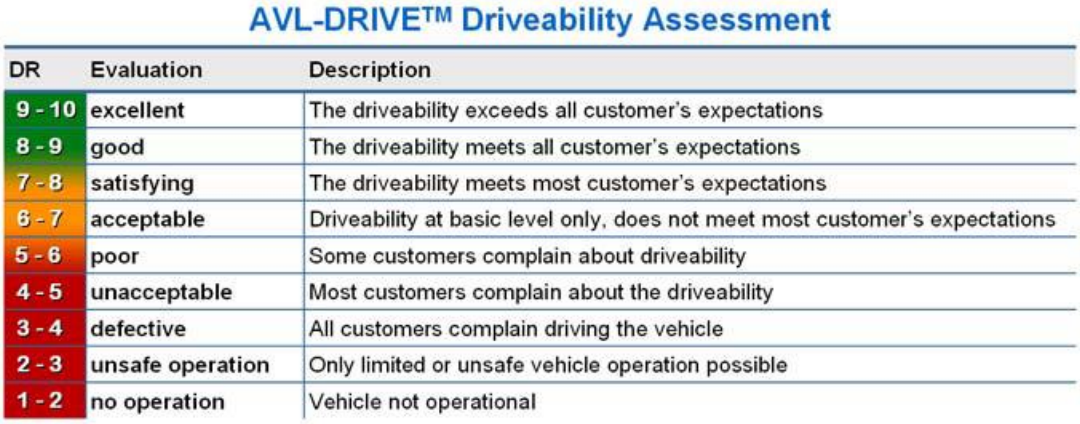
A profound data analysis is accelerated with the help of a graphical representation of the drivability assessment (e.g. time graph, 2D/3D plot, statistical trend analysis, frequency analysis, comparative report). The automatic generation of drivability reports in combination with an automatic creation of benchmark libraries is the key to a fast communication of drivability results.



Nr.	Time [s]	Operation mode
1	442.59 - 446.60	Drive away - Normal
2	446.69 - 450.62	Gearshift - Power-on upshift
3	450.64 - 454.52	Gearshift - Power-on upshift
...		

Figure 6 AVL DRIVE procedure [9]

The drivability itself is assessed at criteria level by means of a DR from 1 to 10 according to the table below, the rating is based on measured/calculated parameter values.



AVL-DRIVE™ Driveability Assessment

DR	Evaluation	Description
9 - 10	excellent	The driveability exceeds all customer's expectations
8 - 9	good	The driveability meets all customer's expectations
7 - 8	satisfying	The driveability meets most customer's expectations
6 - 7	acceptable	Driveability at basic level only, does not meet most customer's expectations
5 - 6	poor	Some customers complain about driveability
4 - 5	unacceptable	Most customers complain about the driveability
3 - 4	defective	All customers complain driving the vehicle
2 - 3	unsafe operation	Only limited or unsafe vehicle operation possible
1 - 2	no operation	Vehicle not operational

Figure 7 DRIVE rating [9]

Higher level drivability assessment such as:

- Sub operation mode
- Main operation mode
- Total drivability index

are calculated by considering weighting factors at criteria and operation mode level. For this purpose, a weight tree is defined for each vehicle type/class. [9]

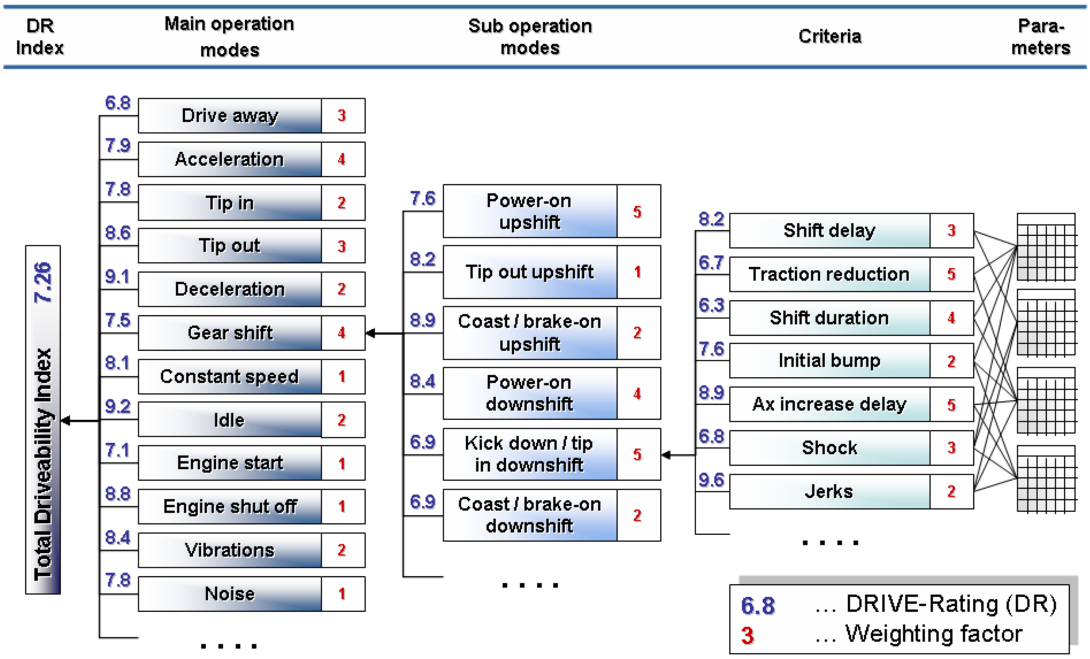


Figure 8 AVL DRIVE weighting factors [9]

In this thesis AVL DRIVE was used after the maneuver was done, given results with an mf4 file or mat file which were prior verified that the data is matching the one from vehicle and that vehicle speed is matching were loaded to AVL DRIVE and DR was evaluated. The main data needed to get DR are all velocities, from car and wheels, engine speed, acceleration, torque, pedal positions and actual and target gear.

3.4. ECU Test

ECU-TEST is a tool used for automatic execution of test cases for automotive software applications developed by TraceTronic GmbH [10]. ECU-Test can be used at every level of the testing phase in the V-cycle, from MiL, HiL up to vehicle testing and it is adaptable to a wide variety of different user-specific toolchains. For my thesis the ECU test was used for the MiL and HiL phase of the V-cycle. ECU test is here functioning as interface between VeriStand and CANape and is providing the given testcycle which should be driven.

For running a test case, ECU-Test requires two configurations, which have to be loaded. The first one is a test configuration file (.tcf), where the vehicle model is described together with all the required models of to be tested control units. The second file is the test bench configuration file (.tbc) where input/output signals are defined, and possible tools and ports can be initialized for control communication. Inside ECU-TEST, a test case is saved in package (.pkg) file, inside a test case can contain other sub-packages or test steps.

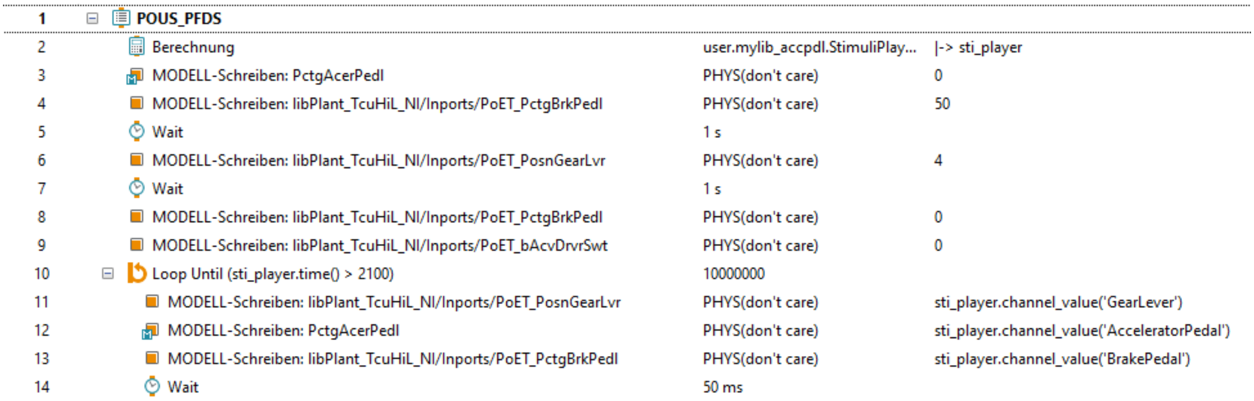
Signal manipulation can be performed in two steps, either a write step or a read-step. In a write-step, a value is assigned to an input signal or model variable, it is also possible to use it to change or assign a calibration value. A read-step can again be divided into four categories:

- model-read,
- measure-read,
- bus-read,
- calibration-read.

For this thesis mainly model write was used, because it was not important to read any signals from ECU test. The signals were just added to the testcase and written by a defined value. The only time where model read is used is by self-generated testcases in cases where a loop has to be broken when a signal is reaching an expected value.

Inside a test step several logical and flow controls can be executed, for instance "If-Then-Else" or "Loop" statements. Some user implemented functions, in terms of arithmetic calculation or Python-written functions, are also optional as test steps. For my thesis only logical controls used were Loops and switch cases, when it was necessary to simulate during a testcase more than one case. A python written function is used just for loading the testcase to ECU test. [11]

Figure 9 is showing part of an ECU test used in this thesis, further explanation on what it shows is described in chapter 6.2.1.2.



1	**POUS_PFDS**		
2	Berechnung	user.mylib_accpdl.StimuliPlay...	|-> sti_player
3	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	0
4	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	50
5	Wait	1 s	
6	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	4
7	Wait	1 s	
8	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	0
9	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_bAcvDrvrSwt	PHYS(don't care)	0
10	Loop Until (sti_player.time() > 2100)	10000000	
11	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	sti_player.channel_value('GearLever')
12	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	sti_player.channel_value('AcceleratorPedal')
13	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	sti_player.channel_value('BrakePedal')
14	Wait	50 ms	

Figure 9 A basic test case package in ECU-TEST

3.5. CANape

CANape [12] is a software tool from Vector Informatik. CANape is widely used by OEMs and ECU suppliers to calibrate algorithms in ECUs at runtime. Primary, the application area of CANape is in optimizing parametrization of electronic control units. During a measurement process it is possible to simultaneously calibrate parameters and record signals. What makes CANape a complete tool for ECU calibration is convenient measurement data evaluation, data management and the possibility to store multiple gigabytes of data per second. CANape also provides access to bus data, diagnostic data and analog measurement data. [13]

Inside this master thesis, CANape is mainly used for collecting all the signal data during a maneuver drive on HiL and save it as an mdf-file. This mdf-file is used inside AVL DRIVE for DR evaluation.

3.6. NI VeriStand

NI VeriStand [14] is a ready-to-use tool that provides a configuration-based software environment to create real-time testing applications including hardware-in-the-loop (HIL) test systems. All of the common functionality necessary for most real-time testing applications, including host interface communication, data logging, stimulus generation, and I/O configuration, is provided by NI VeriStand - ready to configure and use. [15]

3.7.HiL Setup

In general, the setup for the HiL includes the hardware as the base component, TCU and software tools NI Versitand, CANape, ECU test.

TCU has on it the current SW version of the transmission and is via various connections connected to the HiL. These connections are the most important part of the setup, because if here everything is not connected properly the HiL will not work. Just having TCU connected to HiL is not enough for HiL to be ready to run, for this there is a tool necessary. In AVL we used for this NI VeriStand, which is an interface tool between HiL and our plant model, with NI Veristand, TCU and HiL connected is it now possible to drive the vehicle on HiL manually, but there are still missing two parts, one is CANape which is measuring us all the required signals and the other is ECU test which is providing the HiL with testcases so that its driving automatically.

To summarize, all of these five components together make it possible to run the HiL with the same SW as it is in car, run it automatically with all kinds of different testcases and deliver measured data for postprocessing.

4. Plant model

Plant model is a model build in Matlab/Simulink [6], which should represent the vehicle in virtual environment tests. Therefore, the goal for a plant model is, to be built the same way as the vehicle.

Plant model inputs are divided in two parts, the PoET part and the TCU part. PoET inputs are inputs from the environment, such as road gradient, ambient temperature and driver input, which includes pedal position, tip plus, tip minus, etc. TCU inputs are all inputs from the transmission. Output signals from plant model are signals that are required for further data evaluation.

The Plant model is divided into four main subsystems, Plant input generation, Plant xCUs, Plant Powertrain and Plant output generation. The buildup is seen in Figure 10.

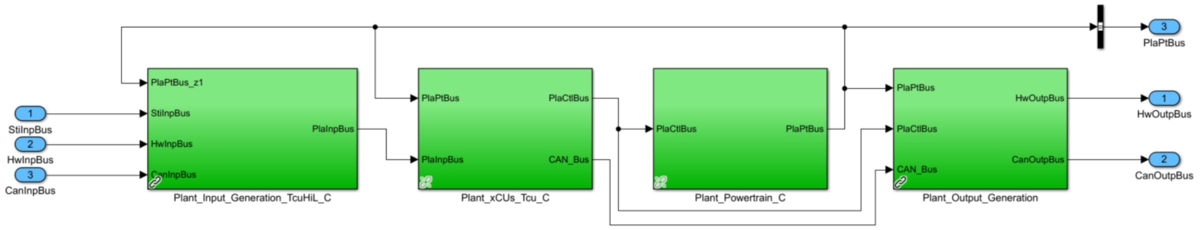


Figure 10 Plant model build up

4.1. Plant input generation

Subsystem Plant input generation has two main responsibilities. The first one is to convert the data type of the inputs. Signals are converted to singles, Booleans or uint8. The second function is to determine if the driver is internal or external. The difference between these two drivers is, that the internal driver has as input just the wished velocity and is driving just to follow this velocity, pedal positions do not interest him. On the other hand, the external driver will drive given the pedal position and will reach velocity which corresponds with given pedal position. For my thesis the external driver is used, because the driver should behave the same as the driver in vehicle and this is possible just with external driver by following the same pedal positions.

4.2. Plant xCUs

The subsystems are “dummy” control units implementing a simplified control logic of the real vehicle controls. The main purpose is to generate the control signals for plant model elements not directly controlled by the real-control unit (e.g. model of Engine Control Unit) and to provide signals to TCU via the powertrain communication network (Rest-Bus simulation). Inputs to Plant xCUs are al driver related outputs for pedal positions and all kind of outputs from plant powertrain, as for example engine toque and speed, velocity, brake pressure etc. Outputs are signals to start the engine, torque demand, clutch current, pedal positions etc.

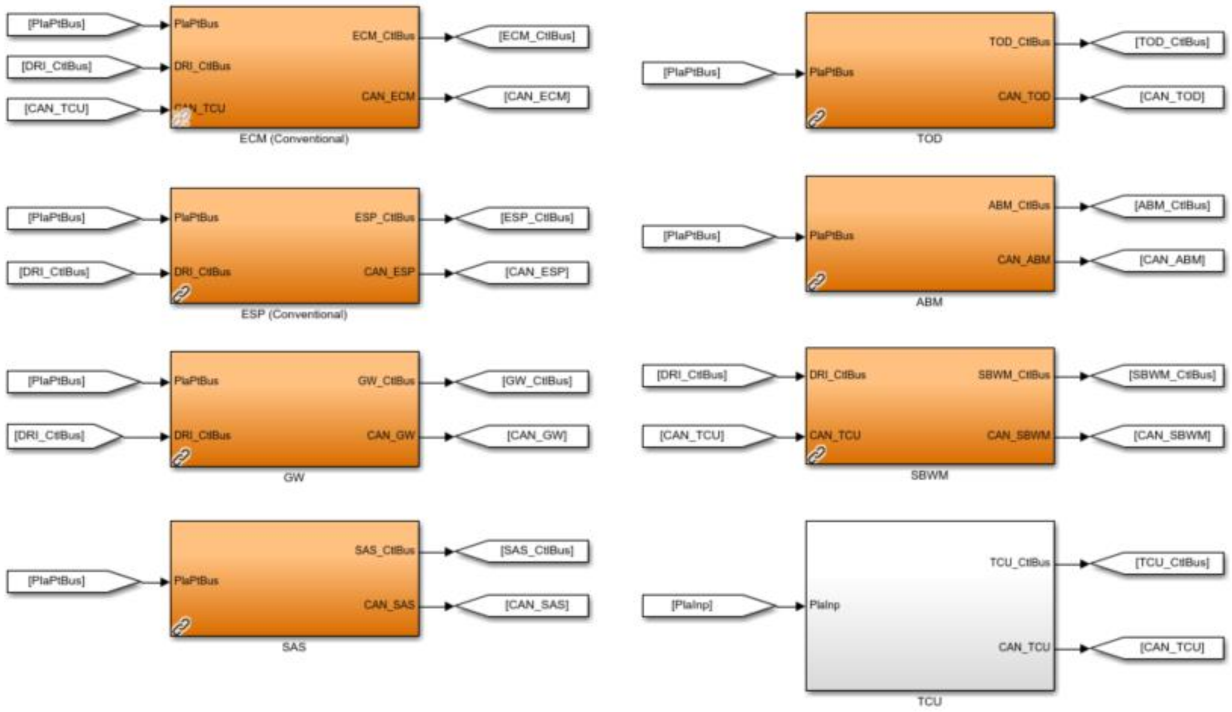


Figure 11 Plant xCUs

4.3. Plant powertrain

Plant powertrain is the main part of the plant model and the most important part for this master thesis. Inside the plant powertrain, the whole powertrain is built and has the main effect for simulation to be as near to real vehicle results as possible. Plant powertrain build up is seen in Figure 12.

Grey subsystems are providing differential equations, torques on clutches, clutch speed and will not be changed for the master thesis.

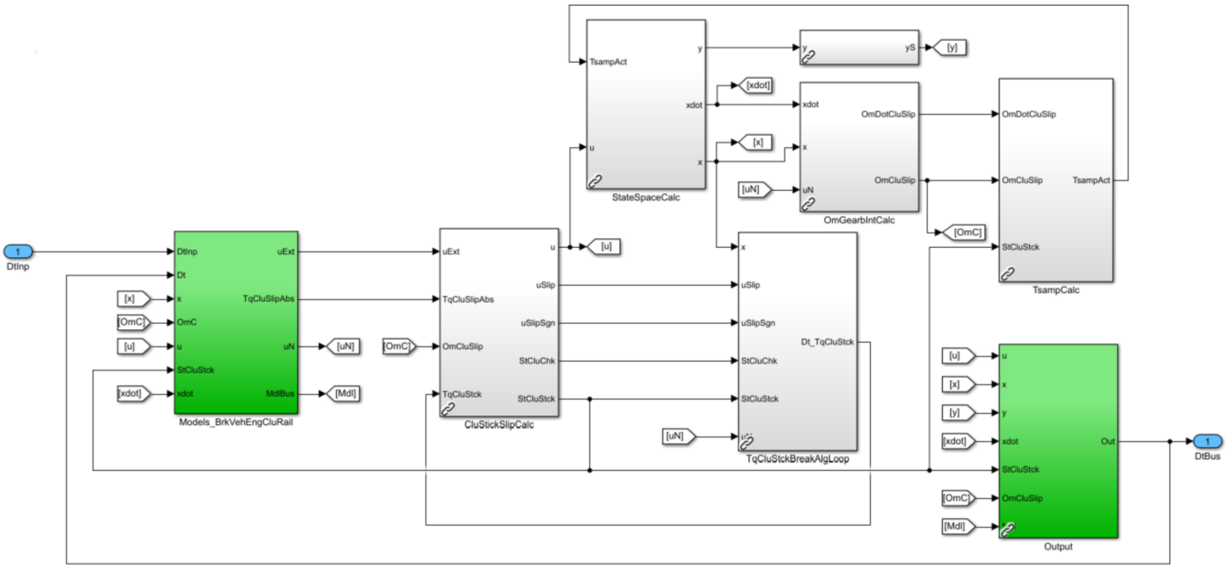


Figure 12 Plant powertrain

Subsystem Models_BrkVehEngCluRail includes all components that are necessary to simulate a powertrain and must be changed for every vehicle. Models inside are depending on what kind of powertrain is under consideration, in AT-9 for example the models are combustion engine, vehicle, gearbox, friction clutch, dog clutch and torque converter. Each of these components is behaving and giving same outputs as the corresponding component in car just that it’s here in virtual environment [16]

The signals needed for these subsystems are all outputs from Plant xCUs, these signals make it together with preloaded constates and parameters possible to provide plant powertrain with enough data to calculate all necessary vehicle data. From engine, torque converter and clutches the torques and speeds and from vehicle the resistances and velocity. The preloaded constants and parameters are mostly vehicle specific data form chapter 2.

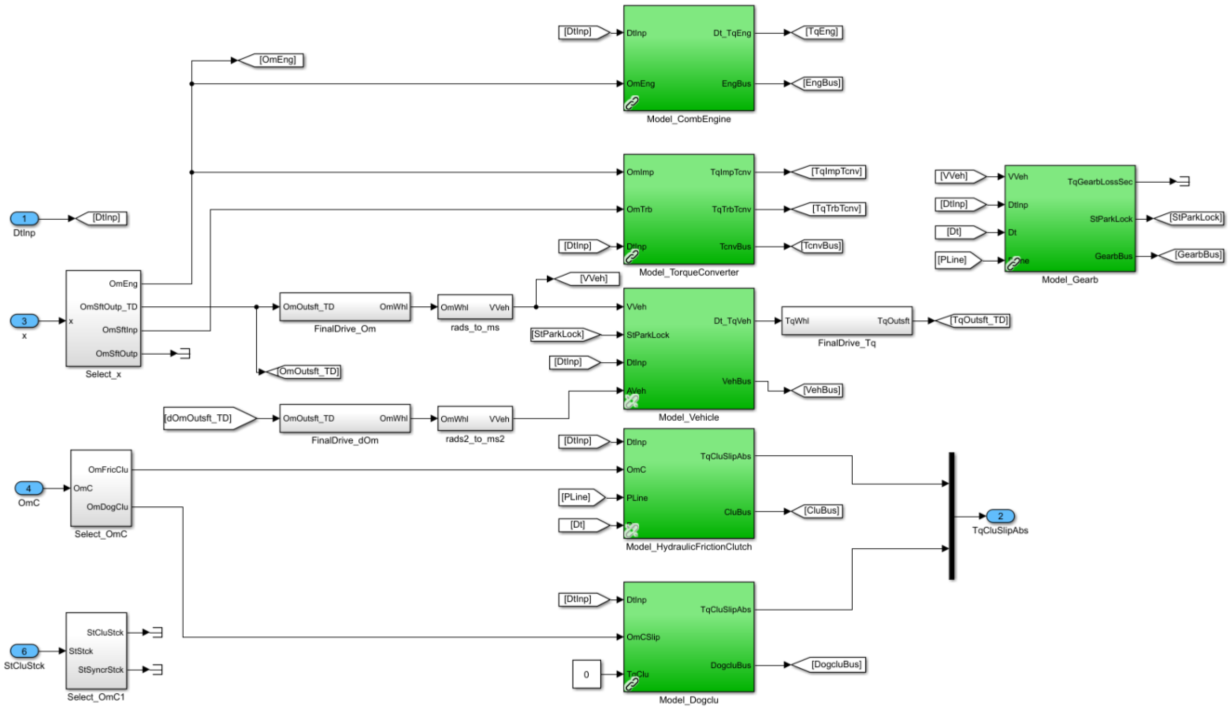


Figure 13 Powertrain models

4.4.Plant output generation

The purpose of Plant output generation subsystem is collecting all generated output signals from previous 2 subsystems and makes them capable for signal evaluation. These signals are more or less being just converted with a MATLAB convert bock and then multiplied with 1.

5. Vehicle measurements

5.1. AT-9 measurements

AT-9 is still a running project during this master thesis, so all the DRIVE measurements which are done in the end of the software development were not driven yet. But still there are some test cases where DR was evaluated and these cases where taken for this master thesis to compare the DR from vehicle tests with DR from the HiL and dummy TCU. It has to be taken into consideration that DR values now are lower than they would be if the measurements would be driven in the end of the project. The reason for this is, that the SW status now is much lower than in the end, so some main functionalities and models are still missing to provide the car with final gearshift management.

5.2.Driven maneuvers for DR evaluation

All driven AVL DRIVE maneuvers follow a specific DRIVE catalogue provided by AVL. The maneuvers are mostly the same for all kind of transmissions, but they may have some minor differences between them. AVL has a catalogue for AT, DCT and AMT transmissions. Described maneuvers bellow apply for AT-9 transmission.

5.2.1. Upshift Power-on D-Mode

Measured events for the maneuver are Drive away - Creep / Normal / Launch and Gearshift - Power-on upshift. The procedure of the maneuver starts with vehicle standstill and gear lever position on D mode. The brake is released and then the pedal has to be set quickly to the wished pedal position. Any over-/undershoot shall be avoided and the pedal is hold constant (<30% pedal: +/- 1% and ≥30% pedal: +/- 2%). The pedal position is kept until the highest gear is reached or the vehicle doesn´t accelerate anymore or max. speed on test track is reached. For each pedal position, the event must be repeated 3 times. Measurement is done with pedal positions 5%, 10%, 15%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%. [17]

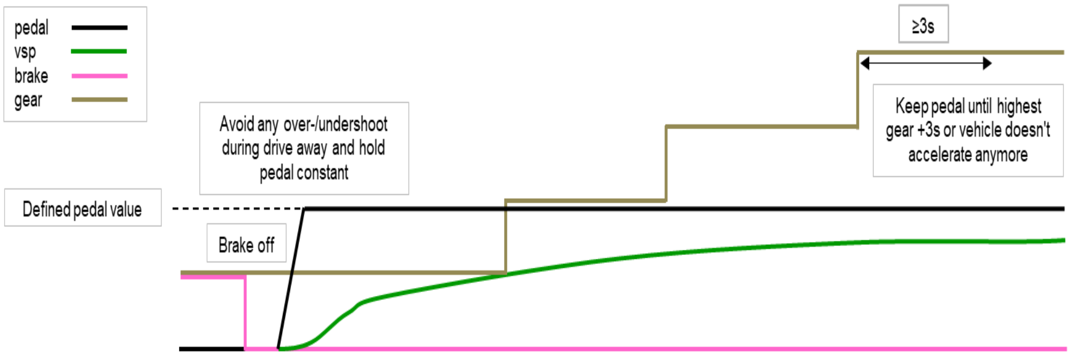


Figure 14 Upshift Power-on Drive-Mode (US_PO_D) [17]

The main criteria to evaluate this drivability is power-on upshift, the DR is evaluated with all power-on upshift gearshifts.

5.2.2. Upshift Tip-out D-Mode Quick

Measured event for the maneuver is Gearshift - Tip out upshift. The procedure of the maneuver starts with vehicle standstill and gear lever position on D mode. Start measurement by holding the defined pedal position (+/- 2%) constant at least 2s before gearshift. The pedal is released quickly at the defined gear and engine speed (lower engine speed has to be taken if auto upshift occurs before tip out). Wait at least 3s for the gear shift to be triggered, then step in again to defined pedal position and repeat the procedure until last gear is reached. Repeat 3 times for each pedal position (50% and 100%). [17]

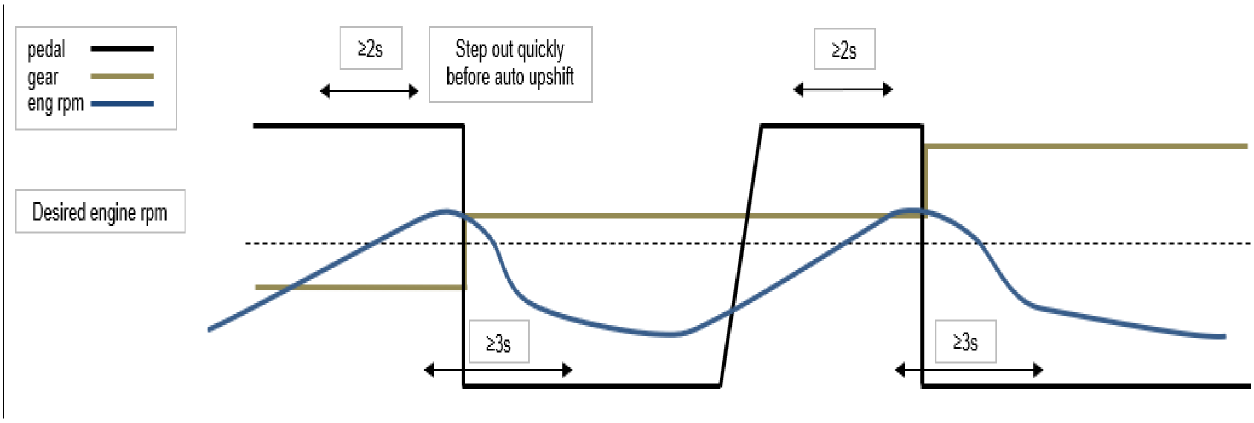


Figure 15 Upshift Tip-out Drive-Mode Quick (US_TO_D_Q) [17]

The main criteria to evaluate this drivability is upshift tip-out, the DR is evaluated with all upshift tip-out gearshifts

5.2.3. Upshift Tip-out D-Mode Slow

Measured event for the maneuver is Gearshift - Tip out upshift. The procedure of the maneuver starts with vehicle standstill and gear lever position on D mode. Start measurement to hold a defined pedal position (+/-2%) constant at least 2s before gearshift. Lift foot slowly at defined gear and engine speed (take lower engine speed if auto upshift occurs before tip out). Wait at least 3s for the gear shift to be triggered, then step in again to the defined pedal position and repeat the procedure until last gear is reached. Repeat 3 times for each pedal position (50% and 100%).

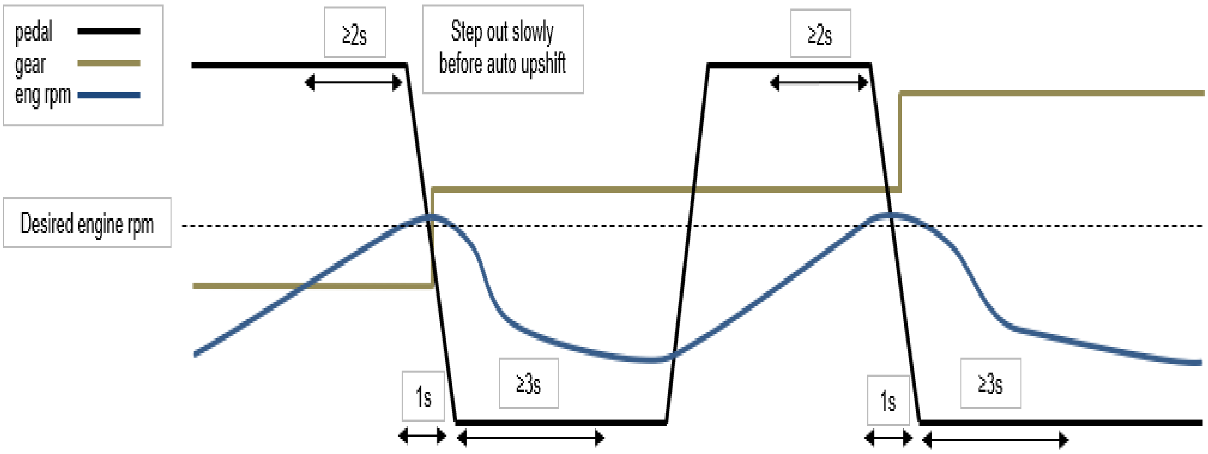


Figure 16 Upshift Tip-out Drive-Mode Slow (US_TO_D_S) [17]

The criteria to evaluate this drivability is the same as for 5.2.2, just that in this case, the tip out is performed within 1 second and not immediately.

5.2.4. Downshift Coast/Brake on D-Mode

Measured event for the maneuver is Gearshift - Coast / brake-on downshift. Start measurement to accelerate to highest gear, step out and coast/push brake to set desired deceleration. Ensure that the defined deceleration (+/- 0.5m/s²) is set at least 2s before downshift. Keep decelerating until lowest gear possible (+3s for gear shift detection) or creep speed. Repeat 3 times for each rate of deceleration (coast, -1m/s^2, -2m/s^2, -3m/s^2). [17]

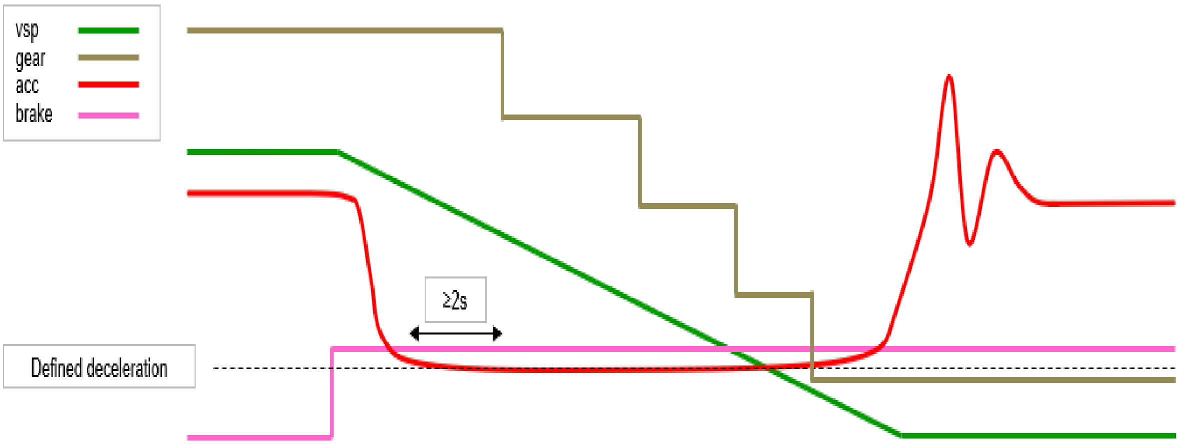


Figure 17 Downshift Coast/Brake on Drive-Mode (DS_CO_D) [17]

The main criteria to evaluate this drivability is downshift coast/brake, the DR is evaluated with all downshift coast/brake gearshifts

5.2.5. Downshift Tip-in D-Mode negative Torque

Measured event for the maneuver is Gearshift - Kick down / tip in downshift. Accelerate from standstill to pre-defined gear and desired engine speed plus a few hundred rpm. Step out and coast for at least 2s, then perform a quick tip in according to defined pedal value (+/- 3%) at desired engine speed (take higher engine speed if auto downshift occurs before tip in). Accelerate to desired engine speed plus a few hundred rpm in next gear, step out, coast for at least 2s and perform next tip in. Repeat 3 times for each pedal position (0 to 70% for 2000rpm and 0 to 100% for 4000rpm). [17]

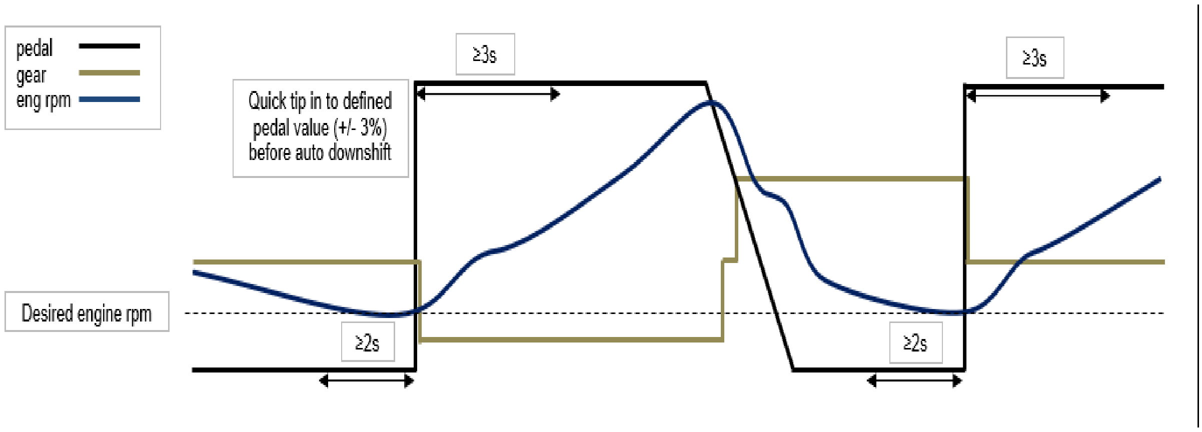


Figure 18 Downshift Tip in Drive-Mode negative Torque (DS_TI_D_N) [17]

The main criteria to evaluate this drivability is downshift tip-in, the DR is evaluated with all downshift tip-in gearshifts

5.2.6. Downshift Tip-in D-Mode positive Torque

Measured event for the maneuver is Gearshift - Kick down / tip in downshift. Accelerate from standstill to pre-defined gear and few hundred rpm below desired engine speed and apply 10% pedal for at least 3s. If vehicle does not accelerate around 0.5m/s² at 10% pedal use higher pedal position (for around 0.5m/s²). Perform a quick tip in according to defined pedal value (+/- 3%) at desired engine speed (take higher engine speed if auto downshift occurs before tip in). Accelerate to desired engine speed minus a few hundred rpm in next gear, apply 10% pedal for at least 3s and perform next tip in. Repeat 3 times for each pedal position (10 to 70% for 2000rpm and 10 to 100% for 4000rpm). [17]

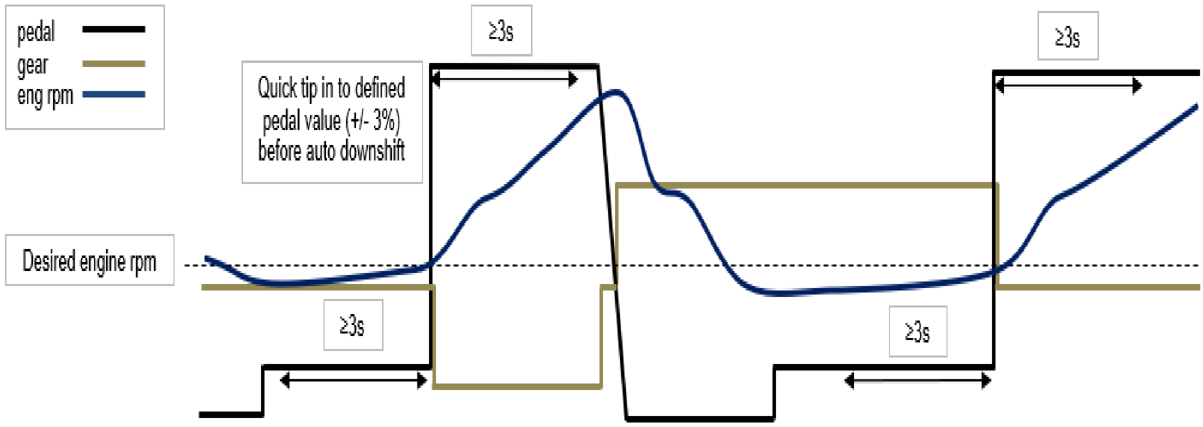


Figure 19 Downshift Tip in Drive-Mode positive Torque (DS_TI_D_P) [17]

The main criteria to evaluate this drivability is downshift tip-in, the DR is evaluated with all downshift tip-in gearshifts

5.3. DR results of vehicle tests

5.3.1. AT-9 results

Because AT-9 is an ongoing project, the results are not so clean and well-structured in different test cases as described in 5.2, nevertheless after looking detailed into the driven test cases, they are still good for comparing the results from HiL, dummy TCU and vehicle. The best cases for this are the following three. The only downside with these test cases is that the only gearshifts driven are Power on Upshift and Power down/Coast Downshift, so there is unfortunately no comparison for the other two gearshifts.

Name of maneuver	**Number of event statuses**	**Drive away DR / Gearshift DR**	**Overall DR**
POUS_50percent_1-5thgear	28	6.0/6.1	6.1
POUS_1-2ndgear_2-3thgear_80_90_100percent	40	6.1/5.8	5.9
POUS_PFDS	350	6.2/5.9	5.9

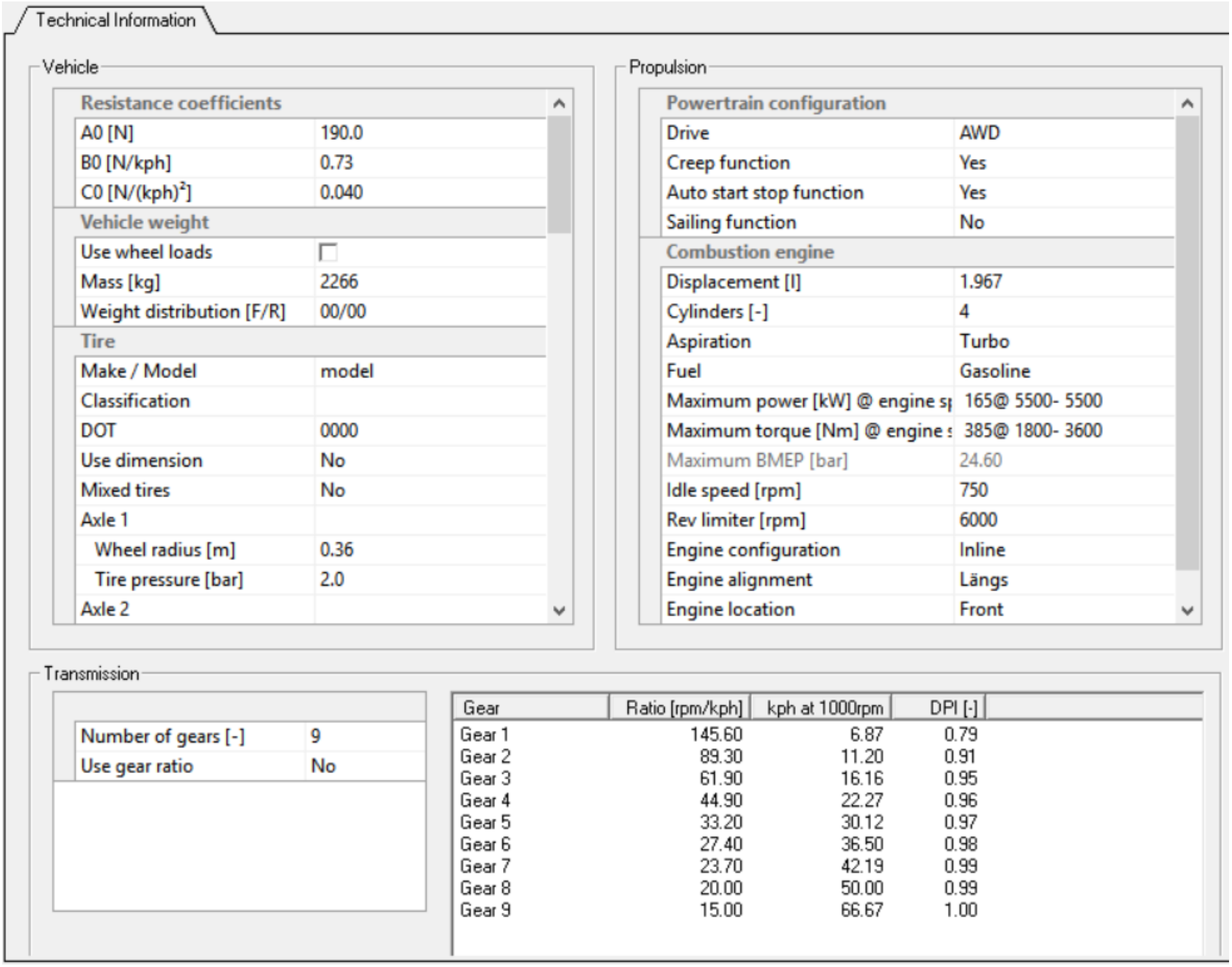
**Table 7 AT-9 DR evaluation*

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

5.4.Data and signals for AVL DRIVE DR evaluation

5.4.1. Technical information

First thing to do for an AVL DRIVE simulation its necessary to fill out the required technical information.



Resistance coefficients	
A0 [N]	190.0
B0 [N/kph]	0.73
C0 $[N/(kph)^2]$	0.040
Vehicle weight	
Use wheel loads	☐
Mass [kg]	2266
Weight distribution [F/R]	00/00
Tire	
Make / Model	model
Classification	
DOT	0000
Use dimension	No
Mixed tires	No
Axle 1	
Wheel radius [m]	0.36
Tire pressure [bar]	2.0
Axle 2	

Powertrain configuration	
Drive	AWD
Creep function	Yes
Auto start stop function	Yes
Sailing function	No
Combustion engine	
Displacement [l]	1.967
Cylinders [-]	4
Aspiration	Turbo
Fuel	Gasoline
Maximum power [kW] @ engine s	165@ 5500- 5500
Maximum torque [Nm] @ engine	385@ 1800- 3600
Maximum BMEP [bar]	24.60
Idle speed [rpm]	750
Rev limiter [rpm]	6000
Engine configuration	Inline
Engine alignment	Längs
Engine location	Front

Number of gears [-]	9
Use gear ratio	No

Gear	Ratio [rpm/kph]	kph at 1000rpm	DPI [-]
Gear 1	145.60	6.87	0.79
Gear 2	89.30	11.20	0.91
Gear 3	61.90	16.16	0.95
Gear 4	44.90	22.27	0.96
Gear 5	33.20	30.12	0.97
Gear 6	27.40	36.50	0.98
Gear 7	23.70	42.19	0.99
Gear 8	20.00	50.00	0.99
Gear 9	15.00	66.67	1.00

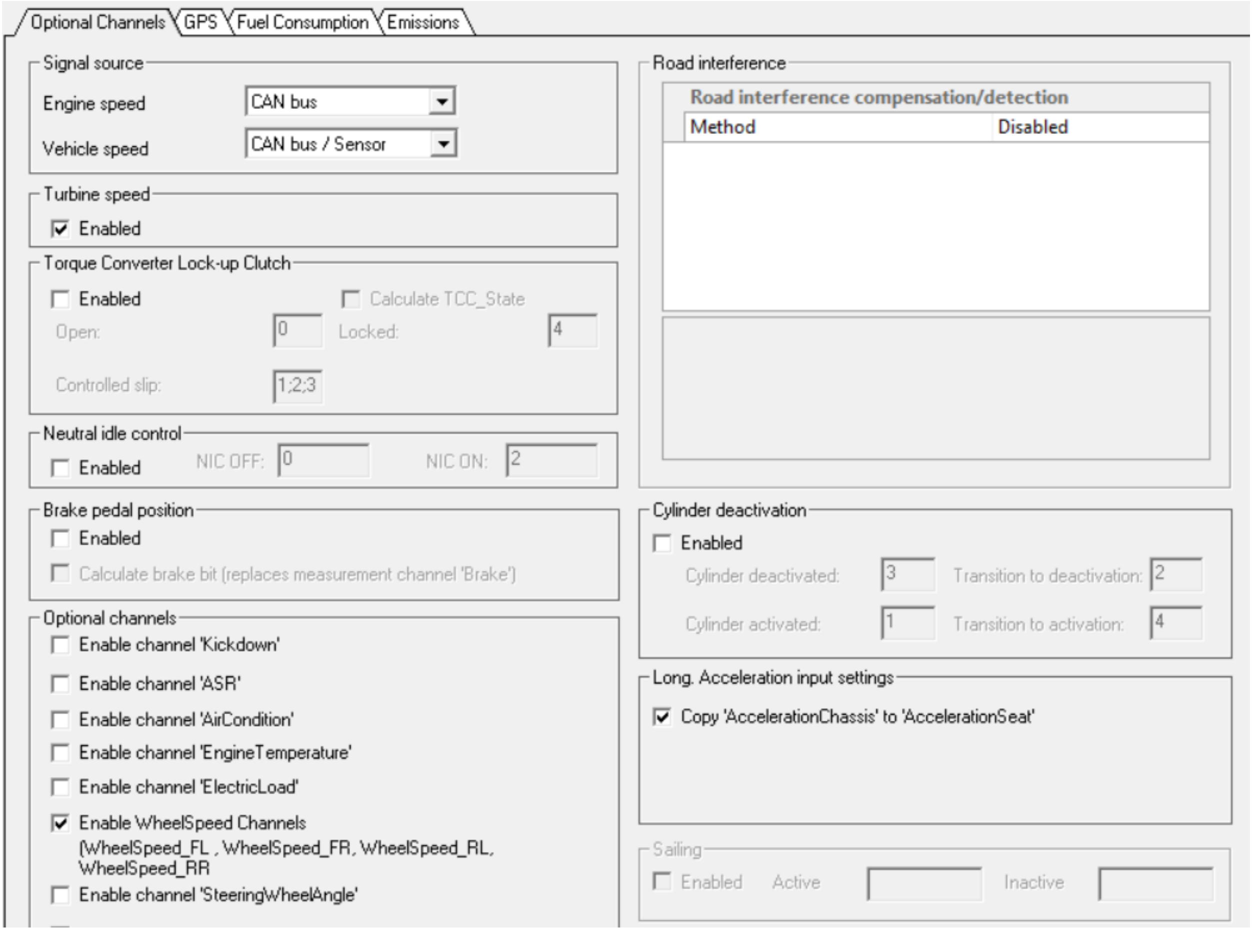
Figure 20 Vehicle Data

The required technical information for AVL DRIVE can be seen in Figure 20. Inside the vehicle part, upper left corner, the required data are the three resistance coefficients, vehicle weight, tire characteristics and vehicle information.

On the upper right corner is the propulsion part. For propulsion, AVL DRIVE needs to know the powertrain configuration and combustion engine properties. Which means, what kind drive train is used, if sailing and creep is possible and if there is an auto start stop function for powertrain and for combustion engine data as displacement, cylinders, aspiration, fuel, idle speed etc. is mandatory.

5.4.2. Used channels in the real vehicle simulation

In AVL DRIVE is it possible to choose between optional settings and additional channels. Optional settings are the ones that if they are enabled for the simulation is it later necessary to add them as signal inputs. Additional channels can be added to the simulation as inputs, but it is not obligatory to add them as inputs, the channel can be left out during the simulation. Adding or removing this channels has not proven to have any effect on the DR during this master thesis. This does not mean that they do not affect the DR, but AVL DRIVE has a lot of different DR evaluations which can be measured and there these signals could provide better knowledge about the overall DR, but for gearshift evaluation it’s the same if this channels are used or not.



Signal source
Engine speed: CAN bus
Vehicle speed: CAN bus / Sensor

Turbine speed
☑ Enabled

Torque Converter Lock-up Clutch
☐ Enabled
☐ Calculate TCC_State
Open: 0
Locked: 4
Controlled slip: 1;2;3

Neutral idle control
☐ Enabled
NIC OFF: 0
NIC ON: 2

Brake pedal position
☐ Enabled
☐ Calculate brake bit (replaces measurement channel 'Brake')

Optional channels
☐ Enable channel 'Kickdown'
☐ Enable channel 'ASR'
☐ Enable channel 'AirCondition'
☐ Enable channel 'EngineTemperature'
☐ Enable channel 'ElectricLoad'
☑ Enable WheelSpeed Channels (WheelSpeed_FL , WheelSpeed_FR, WheelSpeed_RL, WheelSpeed_RR
☐ Enable channel 'SteeringWheelAngle'

Road interference

Road interference compensation/detection	
Method	Disabled

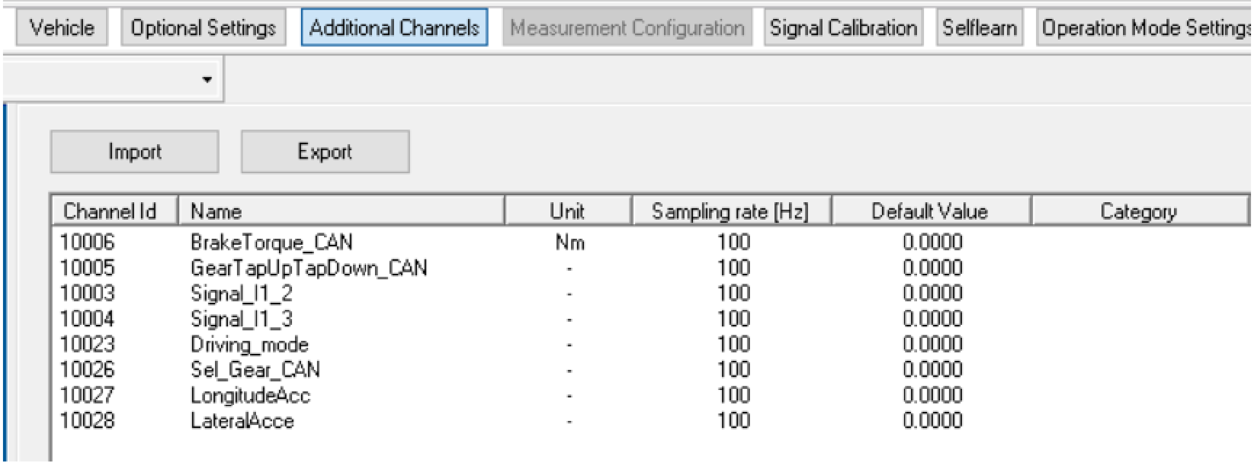
Cylinder deactivation
☐ Enabled
Cylinder deactivated: 3
Transition to deactivation: 2
Cylinder activated: 1
Transition to activation: 4

Long. Acceleration input settings
☑ Copy 'AccelerationChassis' to 'AccelerationSeat'

Sailing
☐ Enabled
Active
Inactive

Figure 21 Optional channels

Inside the optional channels signal source for engine speed and vehicle speed must be chosen, these two signals are mandatory for any kind of AVL DRIVE simulation. All other signals can be enabled or disabled regarding the needs for the specific simulation, these signals can be neutral idle control, brake pedal position, road interference and various optional channels. Optional channels are channels as air condition, wheel speed, engine temperature, engine torque etc.



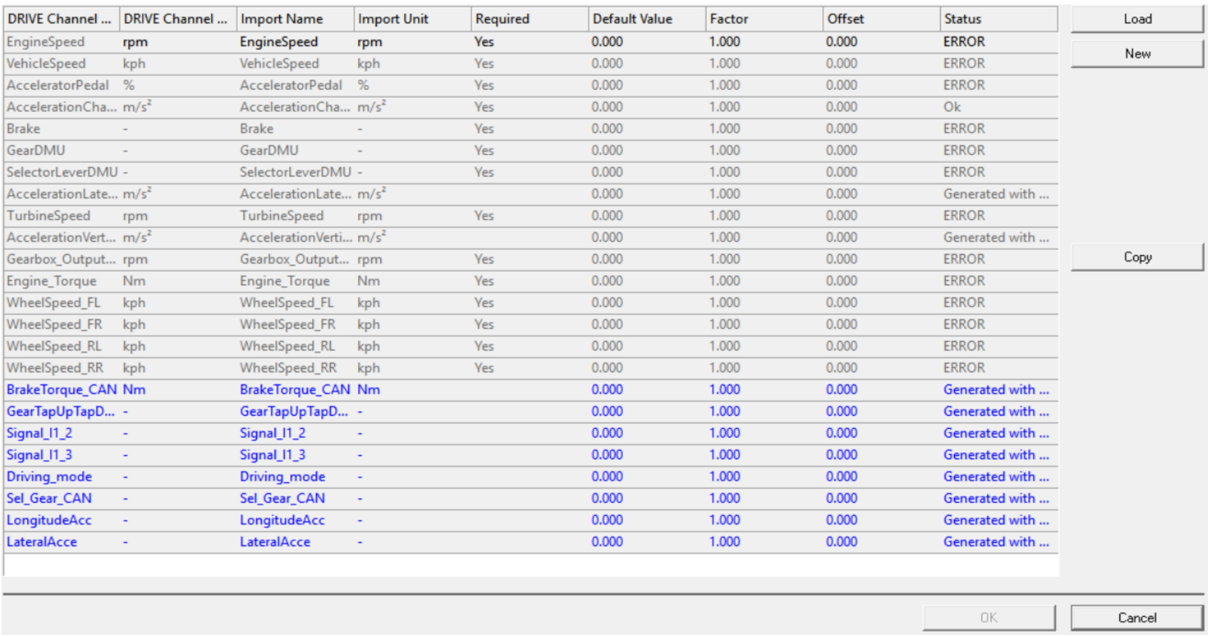
Channel Id	Name	Unit	Sampling rate [Hz]	Default Value	Category
10006	BrakeTorque_CAN	Nm	100	0.0000	
10005	GearTapUpTapDown_CAN	-	100	0.0000	
10003	Signal_I1_2	-	100	0.0000	
10004	Signal_I1_3	-	100	0.0000	
10023	Driving_mode	-	100	0.0000	
10026	Sel_Gear_CAN	-	100	0.0000	
10027	LongitudeAcc	-	100	0.0000	
10028	LateralAcce	-	100	0.0000	

Figure 22 Additional channels

Additional channels are channels, which are not mandatory to be implemented in the simulation but are giving some additional information about the vehicle. Some channels that can be put as additional channel are seen in Figure 22. Additional channels can be imported inside AVL DRIVE or exported and some new channels can be created.

5.4.2.1. Used channels in real vehicle tests

All maneuvers for DR evaluation have been driven with the same configuration of required input channels.



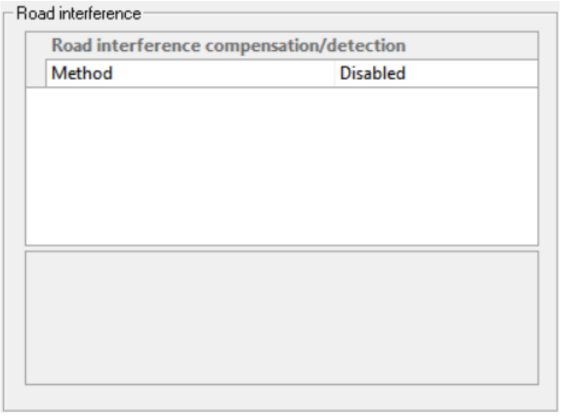
DRIVE Channel ...	DRIVE Channel ...	Import Name	Import Unit	Required	Default Value	Factor	Offset	Status
EngineSpeed	rpm	EngineSpeed	rpm	Yes	0.000	1.000	0.000	ERROR
VehicleSpeed	kph	VehicleSpeed	kph	Yes	0.000	1.000	0.000	ERROR
AcceleratorPedal	%	AcceleratorPedal	%	Yes	0.000	1.000	0.000	ERROR
AccelerationCha...	m/s^2	AccelerationCha...	m/s^2	Yes	0.000	1.000	0.000	Ok
Brake	-	Brake	-	Yes	0.000	1.000	0.000	ERROR
GearDMU	-	GearDMU	-	Yes	0.000	1.000	0.000	ERROR
SelectorLeverDMU	-	SelectorLeverDMU	-	Yes	0.000	1.000	0.000	ERROR
AccelerationLate...	m/s^2	AccelerationLate...	m/s^2		0.000	1.000	0.000	Generated with ...
TurbineSpeed	rpm	TurbineSpeed	rpm	Yes	0.000	1.000	0.000	ERROR
AccelerationVert...	m/s^2	AccelerationVerti...	m/s^2		0.000	1.000	0.000	Generated with ...
Gearbox_Output...	rpm	Gearbox_Output...	rpm	Yes	0.000	1.000	0.000	ERROR
Engine_Torque	Nm	Engine_Torque	Nm	Yes	0.000	1.000	0.000	ERROR
WheelSpeed_FL	kph	WheelSpeed_FL	kph	Yes	0.000	1.000	0.000	ERROR
WheelSpeed_FR	kph	WheelSpeed_FR	kph	Yes	0.000	1.000	0.000	ERROR
WheelSpeed_RL	kph	WheelSpeed_RL	kph	Yes	0.000	1.000	0.000	ERROR
WheelSpeed_RR	kph	WheelSpeed_RR	kph	Yes	0.000	1.000	0.000	ERROR
BrakeTorque_CAN	Nm	BrakeTorque_CAN	Nm		0.000	1.000	0.000	Generated with ...
GearTapUpTapD...	-	GearTapUpTapD...	-		0.000	1.000	0.000	Generated with ...
Signal_I1_2	-	Signal_I1_2	-		0.000	1.000	0.000	Generated with ...
Signal_I1_3	-	Signal_I1_3	-		0.000	1.000	0.000	Generated with ...
Driving_mode	-	Driving_mode	-		0.000	1.000	0.000	Generated with ...
Sel_Gear_CAN	-	Sel_Gear_CAN	-		0.000	1.000	0.000	Generated with ...
LongitudeAcc	-	LongitudeAcc	-		0.000	1.000	0.000	Generated with ...
LateralAcce	-	LateralAcce	-		0.000	1.000	0.000	Generated with ...

Figure 23 Input channels

Figure 23 shows all inputs that were used for real vehicle DR evaluation with AVL DRIVE. Grey highlighted channels are the mandatory ones and must be used during the simulation. The required channels are all accelerations, wheel speeds, engaged gears, pedal positions, engine torque and engine speed. Blue highlighted inputs are optional and if not available can be left out from the AVL DRIVE DR simulation or be set to 0.

5.5. Required channels from HiL for AVL DRIVE

Not all input channels from real vehicle tests can be used for HiL simulation. The reason for this is, that HiL uses a virtual environment and it's not possible to include all environment influences that can be included in real life tests. Road interference is more or less self-explaining why it was disabled, because it's hard to implement road behavior to virtual tests.



Road interference

Road interference compensation/detection	
Method	Disabled

Figure 24 Road interference

Other two channels that are not used for HiL are Lateral acceleration and Vertical acceleration. These two channels cannot be disabled, so they must be implemented in plant model and just be set as a constant value of 0. Disabling of lateral acceleration is done because on the HiL we have just a longitudinal model with no lateral movement. Vertical acceleration could be considered in the future when the model is equipped with proper suspension model.

Figure 25 Accelerations in Simulink

To minimize the effect of all these signals, all the Vehicle measurements have been simulated with AVL DRIVE again, but this time without these signals. This means all future comparison between car and HiL or dummy TCU are made with DR evaluation without these 3 signals.

6. Maneuver preparation for HiL and dummy TCU

6.1. Signal data extraction from AVL DRIVE file

Provided data from AVL DRIVE measurements has several output signals; majority of the signals are the same as the ones which are coming later as outputs from HiL simulations, so they are not needed as inputs. The important signals from AVL DRIVE measurement are:

- Accelerator pedal position
- Brake pedal position
- Gear lever position

This signal values are stored in a .raw file; for the right implementation to HiL, they must be saved into an .csv file.

Because the conversion from a .raw file to .csv is not that straight forward some extra steps have to be implemented. For this master thesis, the conversion has been made with the help of AVL Concerto [18].

All the necessary signals have been loaded into AVL Concerto and then exported to an ASCII file. Getting signal values from ASCII file to .csv is then just a copy-paste procedure. It is important to set the time step in AVL Concerto to 0.1s, so that the interpolation, which has to be done on the HiL, is not too high.

The extracted csv file is then loaded with a python script, as seen in Figure 26, to ECU test.

```
class StimuliPlayer(object):
    def __init__(self, stimuli_file, channels):
        if stimuli_file.endswith('.mat'):
            data = loadmat(stimuli_file)
            for c in channels:
                data[c][1:,0] = data[c][1:,0] + 1e-6*(diff(data[c][:,0])==0)
            self.f = {c: interp1d(data[c][:, 0], data[c][:, 1], bounds_error=False, fill_value='extrapolate') for c in
                        channels}
        else:
            data = read_csv(stimuli_file, skiprows=2, delimiter=';')
            #data = genfromtxt(stimuli_file, dtype=float, usecols=(0,1,2), delimiter='\t', names=True)
            #data = pd.read_csv(stimuli_file, sep = ';', header = 0)
            #print (data)
            self.f = {c: interp1d(data['Time'][:], data[c][:], bounds_error=False, fill_value='extrapolate') for c in channels}
        self.t0 = None
        self.t = 0

    def channel_value(self, channel):
        if self.t0 == None: self.t0 = time.time()
        self.t = time.time() - self.t0
        return float(self.f[channel](self.t))

    def time(self):
        return float(self.t)
```

Figure 26 Python script for signal reading into ECU test

6.2. ECU test package from driven maneuvers

After all test cases are prepared as a csv file and can be successfully read with the Python script, the test cases can be prepared in ECU test.

6.2.1. ECU test package structure

Every package in ECU test has the same structure and it can be divided in three groups, Precondition, Action and Postcondition, the same build up for a test package has been also used for this master thesis.

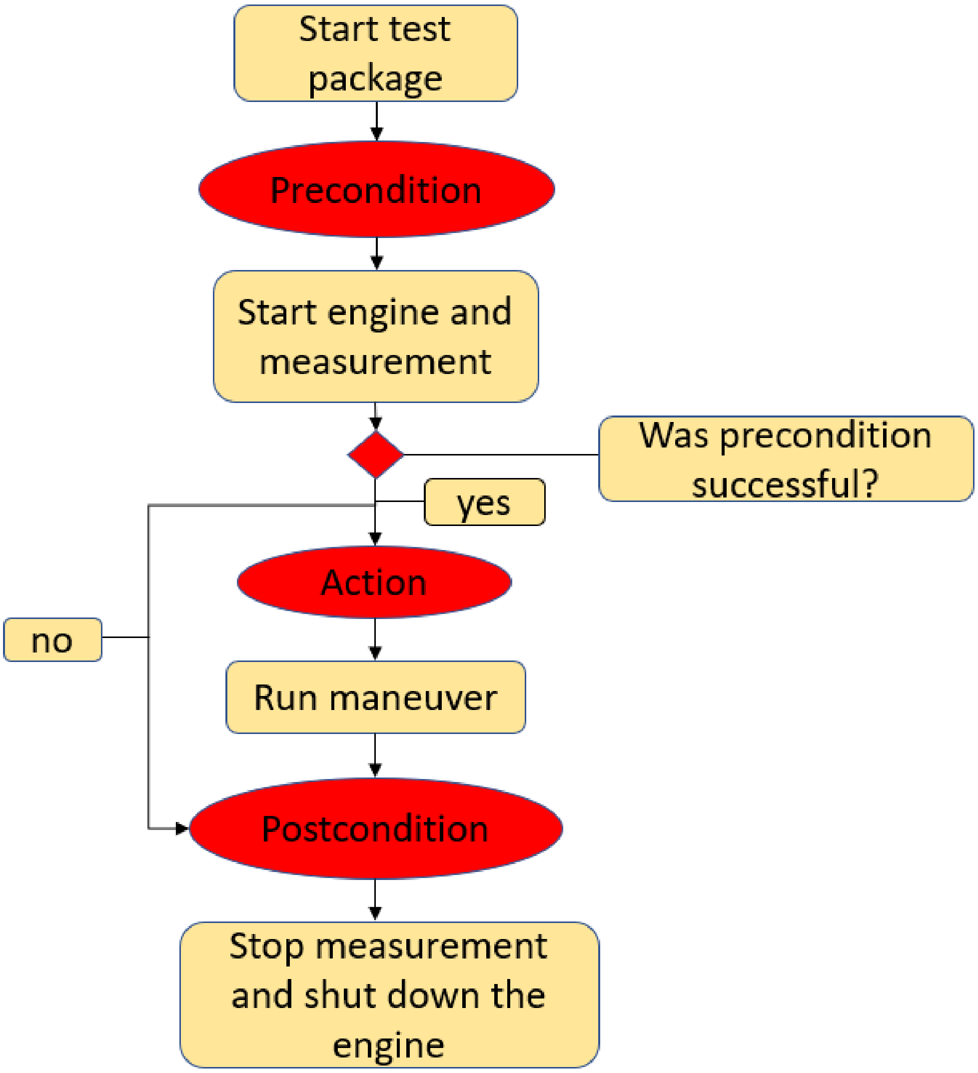
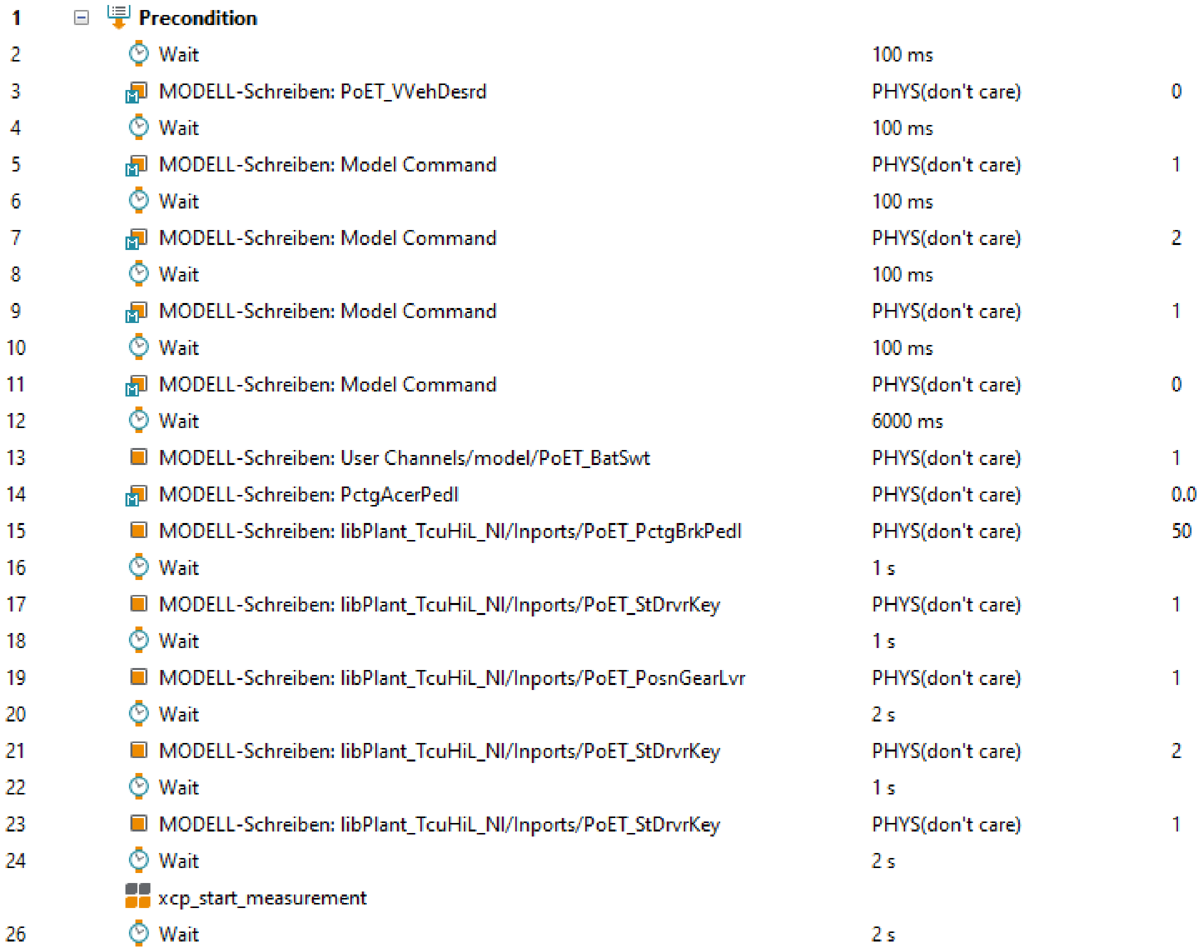


Figure 27 ECU test flowchart of maneuver

6.2.1.1. Precondition

Main purpose for Precondition is to run test package for start measurement and crank the vehicle, so that in Action there is no extra step needed and the test case can start immediately. Figure 28 shows this precondition. The first 10 columns are just basic commands which are needed for HiL to run. In column 13 the battery is switched on and later accelerator pedal position set to 0 and brake pedal to 50, so that in the following 8 columns the engine can be engaged. The second to last column is a package which is starting to record the measurement, so that all the data is stored in one compressed file.



1	**Precondition**		
2	Wait	100 ms	
3	MODELL-Schreiben: PoET_VVehDesrd	PHYS(don't care)	0
4	Wait	100 ms	
5	MODELL-Schreiben: Model Command	PHYS(don't care)	1
6	Wait	100 ms	
7	MODELL-Schreiben: Model Command	PHYS(don't care)	2
8	Wait	100 ms	
9	MODELL-Schreiben: Model Command	PHYS(don't care)	1
10	Wait	100 ms	
11	MODELL-Schreiben: Model Command	PHYS(don't care)	0
12	Wait	6000 ms	
13	MODELL-Schreiben: User Channels/model/PoET_BatSwt	PHYS(don't care)	1
14	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	0.0
15	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	50
16	Wait	1 s	
17	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_StDrvrKey	PHYS(don't care)	1
18	Wait	1 s	
19	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	1
20	Wait	2 s	
21	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_StDrvrKey	PHYS(don't care)	2
22	Wait	1 s	
23	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_StDrvrKey	PHYS(don't care)	1
24	Wait	2 s	
	xcp_start_measurement		
26	Wait	2 s	

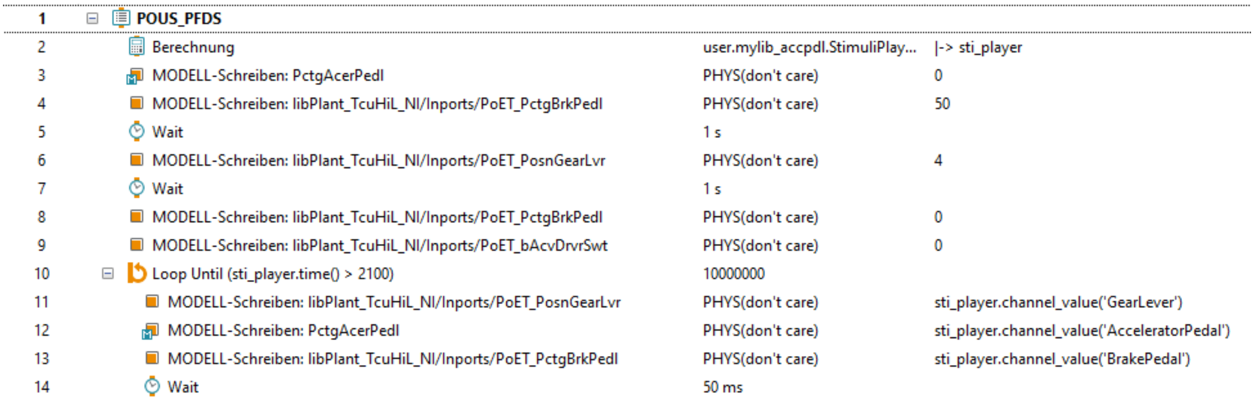
Figure 28 ECU Test package Precondition

6.2.1.2. Action

Action is the main part of a test package, here are happening all the main steps during a test case and all the data, which is evaluated is coming out of Action. This data are all signals needed later for AVL DRIVE evaluation and can be seen in figure 23.

At first a calculation is implemented, which reads the Python script and puts all the necessary data from the csv file into ECU test package. Next important thing before the actual test case can be driven is to select the driver. If the driver is internal, driver switch must be on 0 if not, then on 1. Internal driver is used just if the test case starts at given velocity and the vehicle has to accelerate to defined velocity, during the main manoeuvre, the driver is always external.

The actual test case is just a loop over the time, which has been driven during a real vehicle test and inside this loop after every 50ms a new data for accelerator pedal, brake pedal and gear lever is selected. The whole Action process can be seen in Figure 29

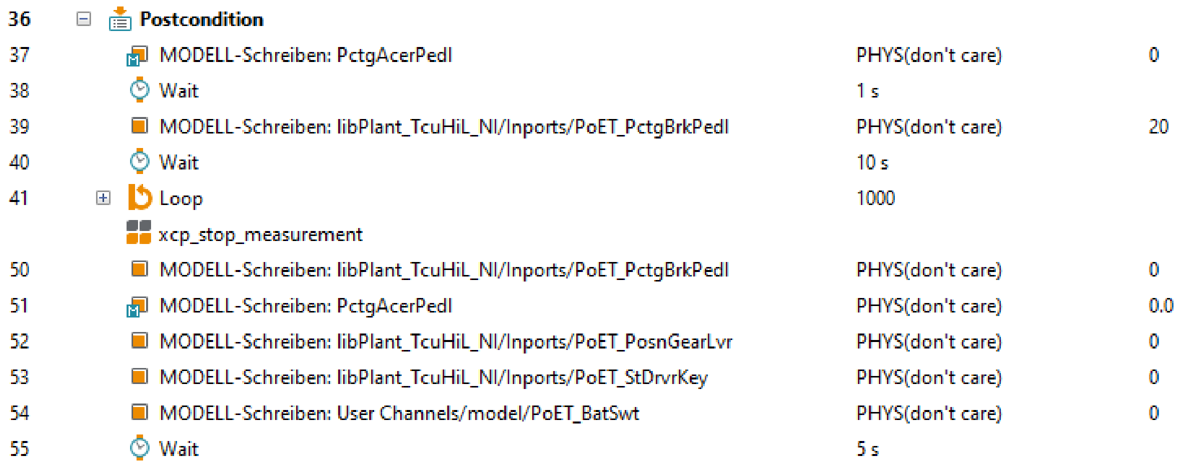


1	**POUS_PFDS**		
2	Berechnung	user.mylib_accpdl.StimuliPlay...	|-> sti_player
3	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	0
4	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	50
5	Wait	1 s	
6	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	4
7	Wait	1 s	
8	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	0
9	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_bAcvDrvrSwt	PHYS(don't care)	0
10	Loop Until (sti_player.time() > 2100)	10000000	
11	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	sti_player.channel_value('GearLever')
12	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	sti_player.channel_value('AcceleratorPedal')
13	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	sti_player.channel_value('BrakePedal')
14	Wait	50 ms	

Figure 29 ECU Test package Action

6.2.1.3. Postcondition

Postcondition is in the end just running stop_measurment test package, to end the test case and to properly shut down the vehicle, so that in the start of next test case there are no unexpected errors.



36	**Postcondition**		
37	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	0
38	Wait	1 s	
39	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	20
40	Wait	10 s	
41	Loop	1000	
	xcp_stop_measurement		
50	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PctgBrkPedl	PHYS(don't care)	0
51	MODELL-Schreiben: PctgAcerPedl	PHYS(don't care)	0.0
52	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_PosnGearLvr	PHYS(don't care)	0
53	MODELL-Schreiben: libPlant_TcuHiL_NI/Inports/PoET_StDrvrKey	PHYS(don't care)	0
54	MODELL-Schreiben: User Channels/model/PoET_BatSwt	PHYS(don't care)	0
55	Wait	5 s	

Figure 30 ECU Test package Postcondition

6.3. Simulink test case from driven maneuvers

Test case preparation in Simulink is much easier than it is on ECU test for HiL. For the 3 mayor signals, accelerator pedal, brake pedal and gear lever, look-up tables are created to load the data from Excel to the model and the driver switch can be switched between 0 and 1, regarding if predefined velocity to the measurement is necessary. If predefined velocity is given, the desired velocity constant is changed accordingly and the time how long the switch should be on 0 is set. Road gradient, gear request and lock-up clutch constants are always on 0 and the driver key on 2. The implementation of the described Simulink signals can be seen in Figure 31.

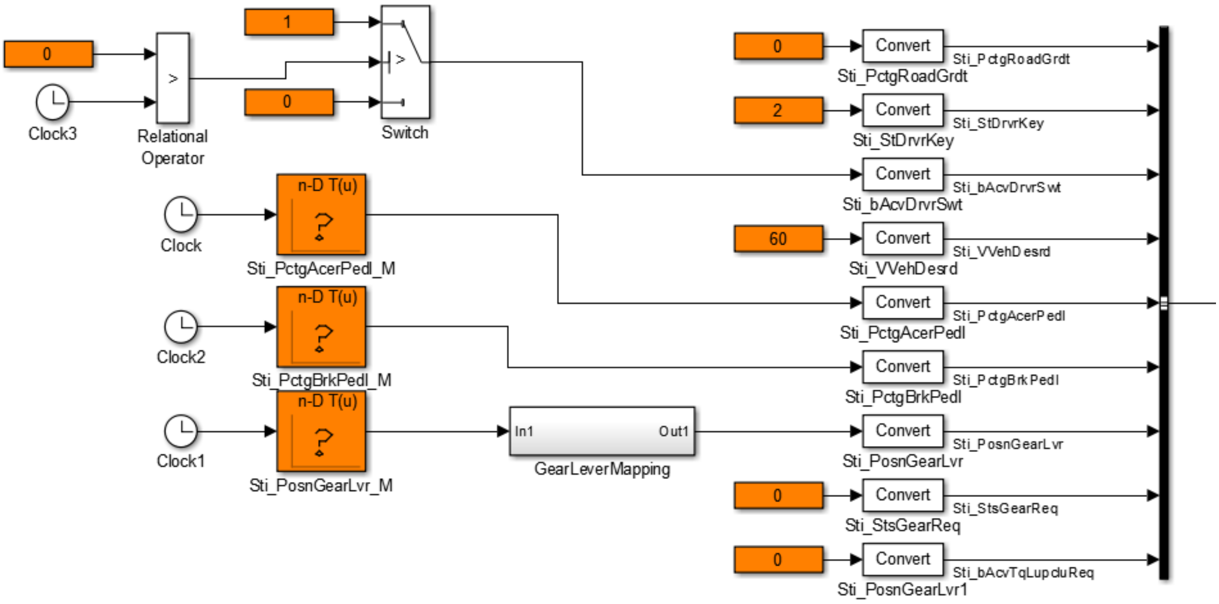


Figure 31 Simulink test case for driven maneuvers

7. Velocity profile evaluation of the original Plant model

Before doing AVL DRIVE simulations of manoeuvres it’s important to get velocity profiles from HiL and dummy TCU compared to the car measurements as similar as its possible, the velocity deviation should be around +/- 2 km/h, it’s hard to estimate the highest allowed velocity deviation, but 2 km/h should be low enough to not cause any DR differences. Because gearshifts influence velocity, torque and pedal position dependent and if the velocity is not matching, this leads also to torque profile being miscalculated and therefor gearshifts are not the same and do not happen on the same time, which makes the AVL DRIVE evaluation to compare two measurements useless.

7.1.AT-9 dummy TCU velocity profile

Achieving the right profiles in At-9 was a bit challenging. Because the project is ongoing and there were not so many tests done with the Plant model, there were quite a bit of improvements to be done.

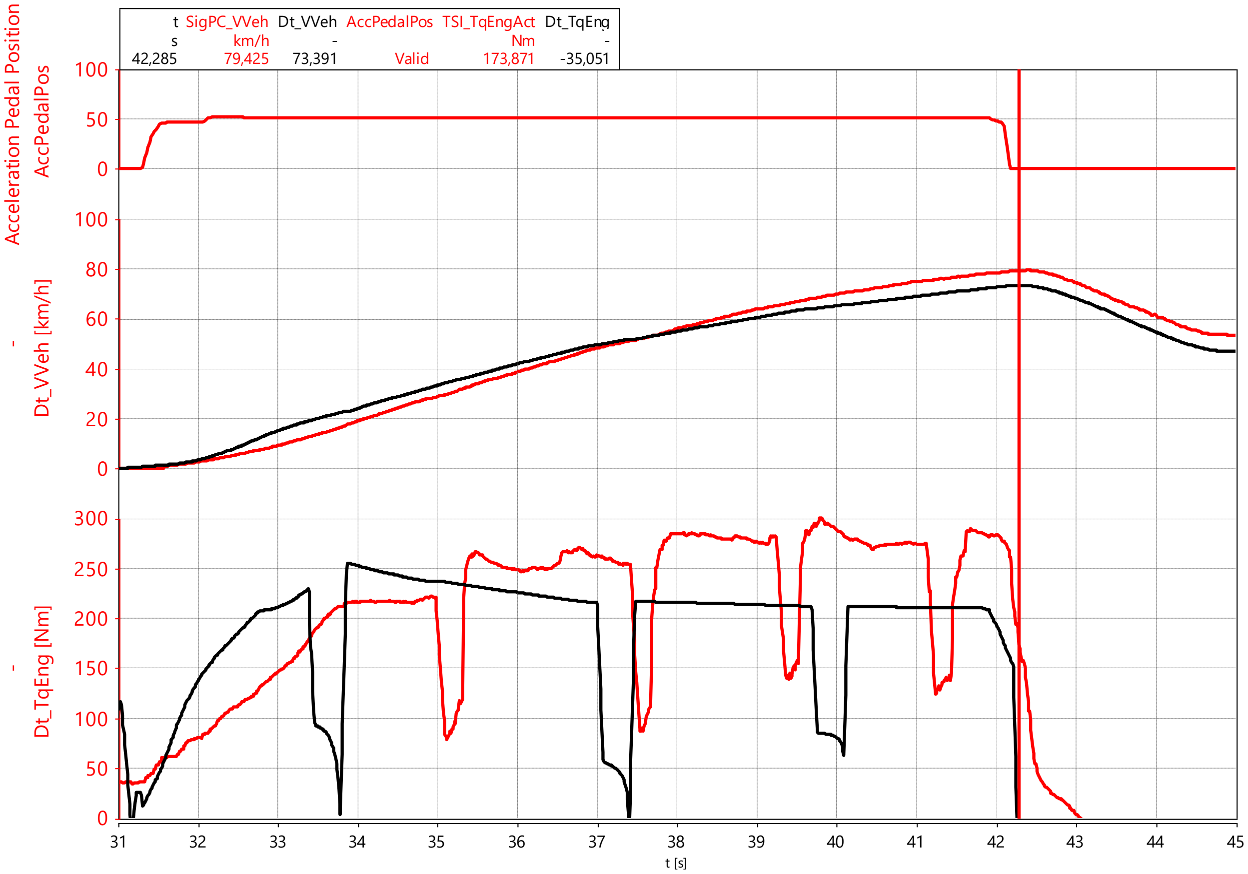


Figure 32 Velocity profile dummy TCU-POUS 50perc (1)

After first look in the profile seen in Figure 32, where red line is the car measurement and black one dummy TCU simulation. There are two main problems with this profile looking just how torque is affecting it. The first one is, that the torque is with higher velocity decreasing instead of increasing and the second one is, that after tip in, the torque is rising way to fast, the torque increase can be clearly seen between seconds 31 and 34.

For both problems there is one solution that was implemented inside the model. For torque decreasing the assumption was that the pedal map may be false. After looking inside the model where pedal map is implemented, seen in Figure 33, the assumption was that the maps for high velocity and low velocity may be switched.

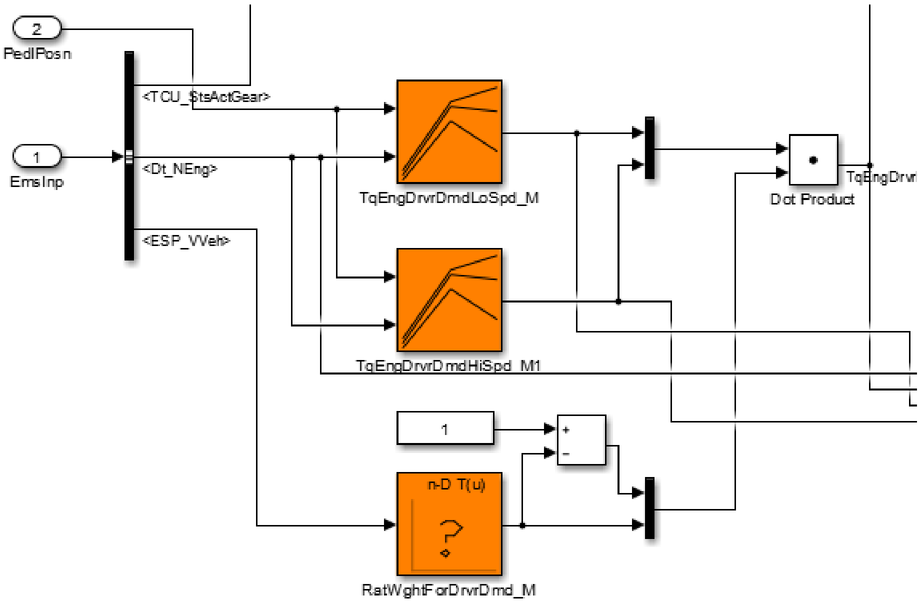


Figure 33 Pedal map calculation

Regarding too fast torque rise after tip in, a rate limitation is implemented, which is causing that after fast tip-in the torque is rising slower than before. Implemented rate limitation can be seen in Figure 34.

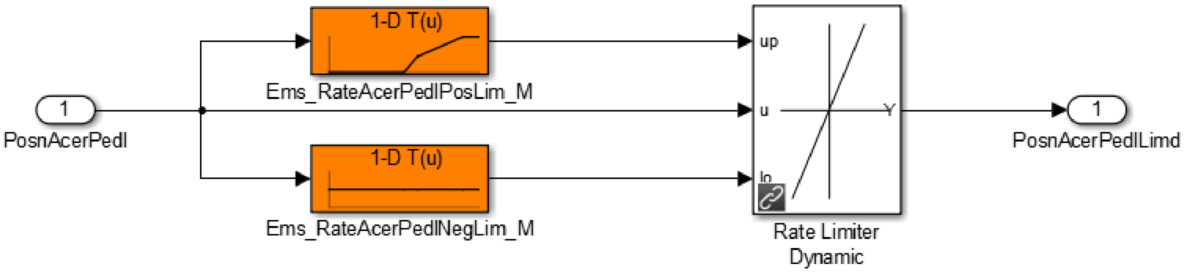


Figure 34 Rate limitation for pedal position

The rate limitation is divided in 4 parts, because the pedal in the car is not rated the same in every pedal position, so there is a different rate limitation for 20%, 50% and 90% pedal position. After changing the model for better torque profile, the velocity profile did change a bit but still not to the wished level.

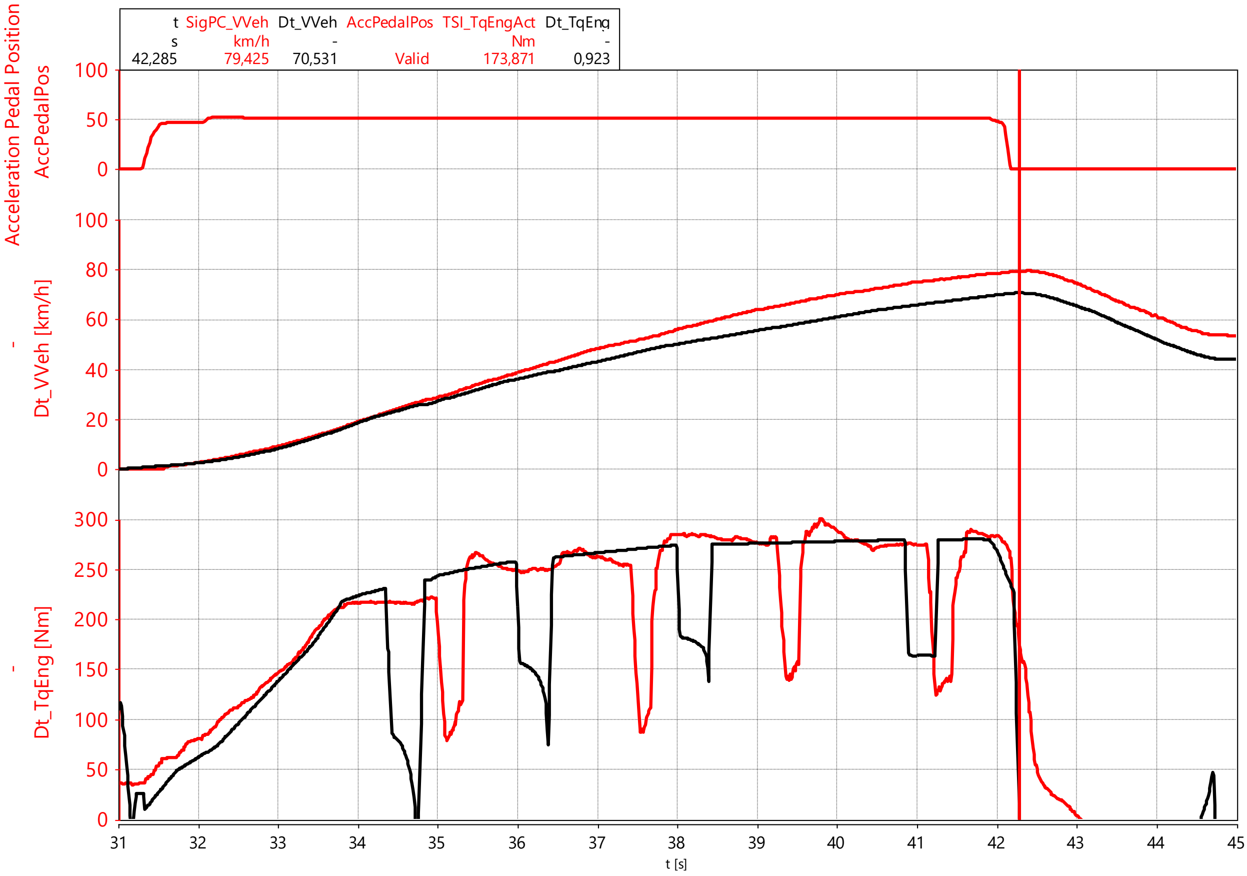


Figure 35 Velocity profile dummy TCU-POUS 50perc (2)

Additional reason for this are the gearshift points. As seen in Figure 36, the dummy TCU is changing gears sooner the real car.

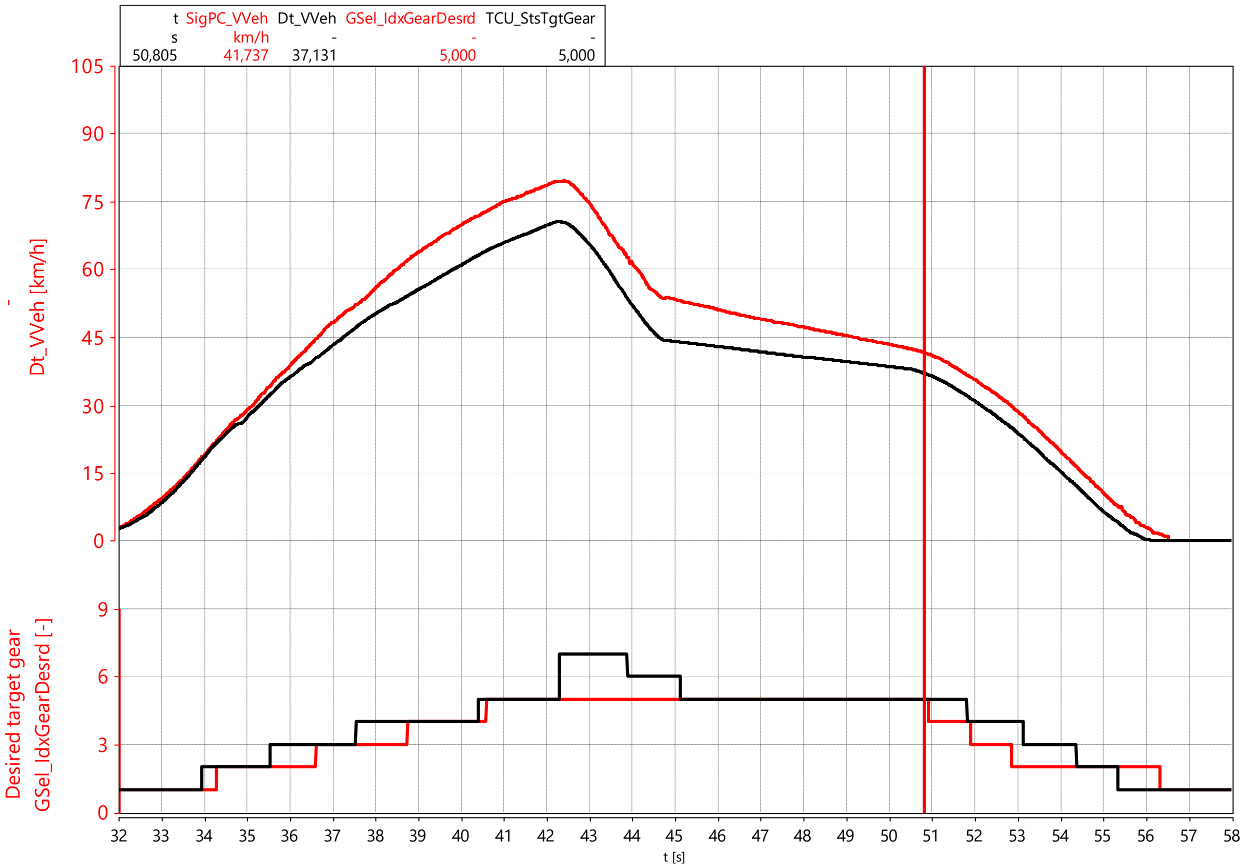


Figure 36 Velocity profile dummy TCU-POUS 50perc (3)

For correcting this, the car data are read out at which output shaft speed gearshift should have happened and the gearshift map has been chanced accordingly. Velocity profile with new torque profile and correct gearshift points can be seen in Figure 37.

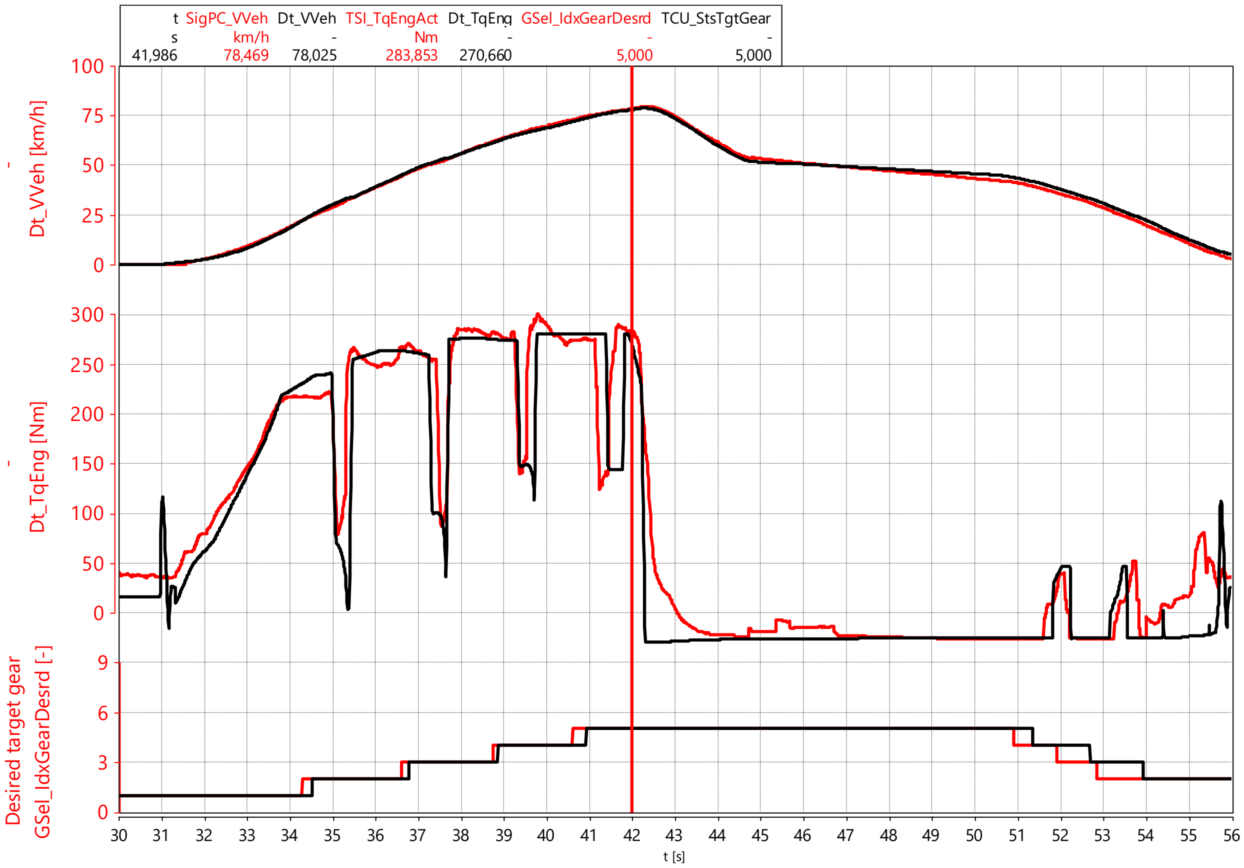


Figure 37 Velocity profile dummy TCU-POUS 50perc (4)

This profile is followed nearly perfect and model like this can be used for DR evaluation.

By looking at the engine torque profile, following differences can be still noticed between measured and simulated behavior:

1. Torque peak at beginning of maneuver in simulation, while the measurement shows a smooth behavior
2. Torque overshoot in measurement after the end of torque intervention, not seen in simulation
3. Fast engine torque reduction after transition power-on to power-off in simulation, whereas measurement show a drop of torque in about 2 seconds
4. Slightly different torque intervention requests, especially in first shifts (1-2 and 2-3)

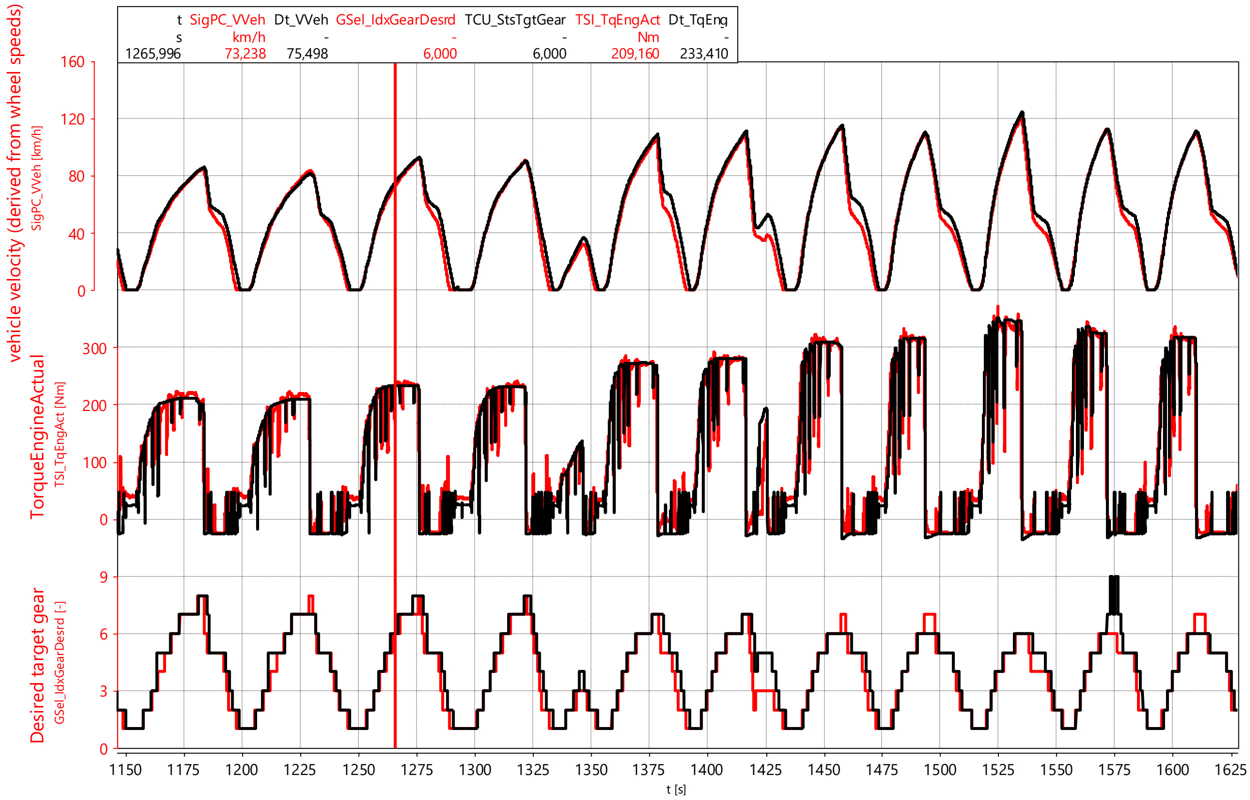


Figure 38 Dummy TCU velocity profile POUS_PFDS

Figure 38 shows the effect of model changes for torque and gearshift in another maneuver, where it can also be seen that the velocity profile is followed good. Some differences are observed in braking behavior (braking model is rather simple) and shift strategy in some part of the simulation.

7.2.AT-9 velocity profile

All Plant model changes that were done for the dummy TCU affect HiL simulations in the same way, so it was not necessary to modify it additionally to get the wished velocity profile.

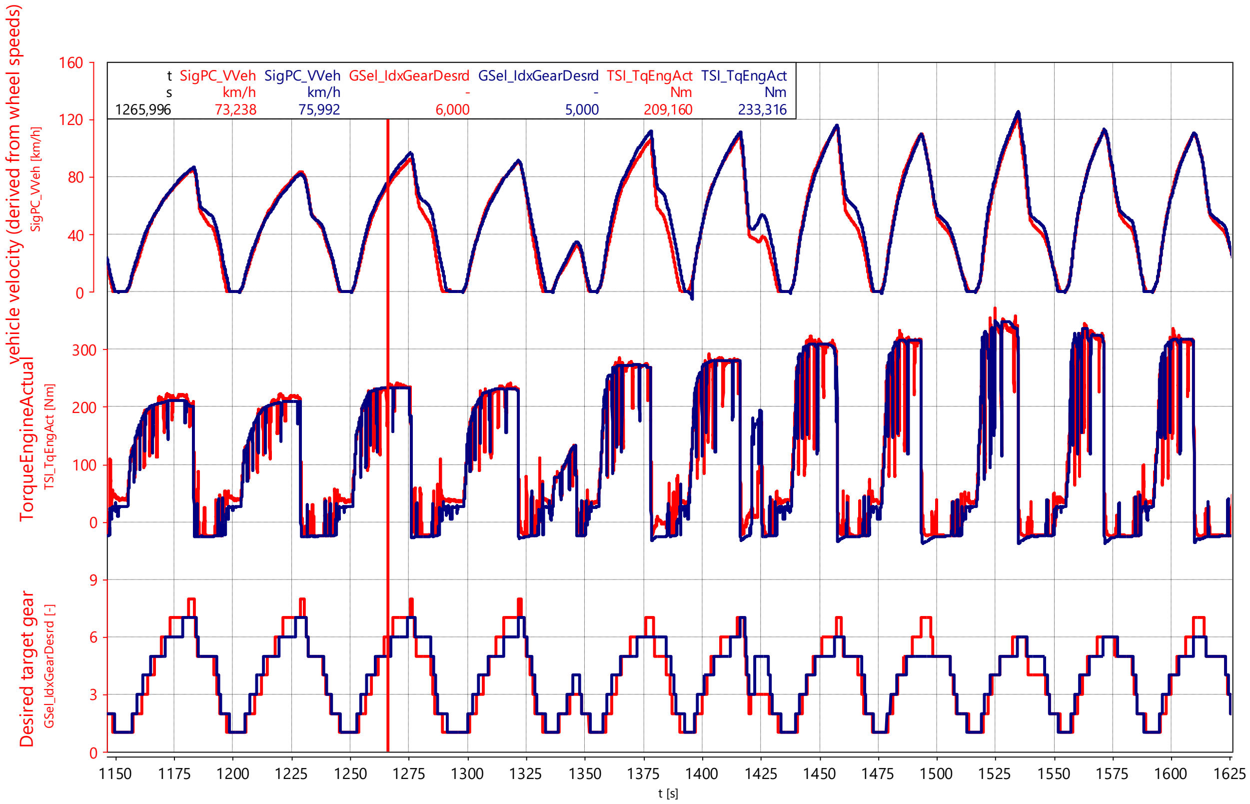


Figure 39 HiL velocity profile POUS_PFDS

8. First DR evaluation

Evaluation of the test cases has not been done with the main 6 test cases as it is described in chapter 5.2, because the project is not in the phase yet to evaluate full AVL Drive test cases. But provided measurements are evaluating the two most common gearshifts, Power up Downshift was measured but the simulations on HiL and dummy TCU deliver some problems which are seen and described in chapter 8.1.3 and Power down Upshift was not even measured.

The evaluation is done with comparing the DR of each simulation between car measurements and dummy TCU or HiL. The status of the Plant model here is the same as the one from chapter 7 with all the adjustments for following the exact velocity profile.

Testcase	Status
US_PO_D	Driven and considered
DS_CO_D	Driven and considered
US_TO_D_Q	Not driven
US_TO_D_S	Not driven
DS_TI_D_N	Driven and not considered
DS_TI_D_P	Driven and not considered

Table 8 Considered testcases in the simulation

8.1.1. AT-9 dummy TCU Gearshift Power on upshift

DR for Power on upshifts are overall not so far away if compared car with dummy TCU. To have better understanding of how good DR comparison really is, it is important to compare each gearshift separately or at least compare gearshifts with the same pedal position.

For evaluating the gearshifts, they were separated in 3 parts regarding on the pedal position, for better representation what is causing DR deviation for each part, because the problems for pedal position 10% pedal position may not be the same as for 100%.

8.1.1.1. Low Pedal positions

This section is covering the peal positions from 5% to 25%. In this section, the DR in lower gears is much smaller with dummy TCU and in higher gears to high. Most of the reasons for this are engine torque and acceleration behavior, which are further explained in chapter 9.1.

**Table 9 Dummy TCU DR in low pedal positions*

Gearshift	**Car DR**	**Dummy TCU DR**
1-2	7.4	6.1
2-3	7.5	6.1
3-4	7.2	8.2
4-5	6.8	8.8
5-6	7.2	8.5
6-7	7.6	8.2
overall	7.2	6.5

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.1.2. Mid pedal positions

Mid pedal positions are covering pedal positions from 30%-60%. DR behavior is similar to the one in low pedals with problems on engine torque and acceleration side. Further explanation to why this happens is described in chapter 9.1.

**Table 10 dummy TCU DR in mid pedal positions*

Gearshift	**Car DR**	**Dummy TCU DR**
1-2	6.8	5.0
2-3	6.1	5.2
3-4	6.6	6.3
4-5	7.0	7.5
5-6	6.0	8.3
6-7	7.4	8.1
overall	6.4	5.5

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.1.3. High pedal positions

High pedal positions are all positions above 60%. In this section, the difference between DR in car and dummy TCU is smaller than in previous two sections. Further explanation can be seen in chapter 9.1

**Table 11 Dummy TCU DR in high pedal positions*

Gearshift	**Car DR**	**Dummy TCU DR**
1-2	6.0	5.5
2-3	6.3	5.7
3-4	6.2	6.7
4-5	6.3	6.9
overall	6.2	5.8

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.1.4. Conclusion

After looking just at the DR for Power on upshift for all three sections its clearly seen similar behavior, with lower DR happening in lower gears and after gearshifts 3 to 4 the DR is suddenly rising to value above DR measured in car. So, the main goal is to find what is causing this behavior of DR and will be discussed in chapter 9.1.

8.1.2. AT-9 dummy TCU Gearshift Coast/Brake on downshift

Downshift DR evaluation seems good and the difference of 0.5 DR is not high. Main reason for better behavior may be constant load during the whole downshift process, so the big differences which happen during upshift do not apply for downshift.

**Table 12 Dummy TCU DR Downshift*

Name of maneuver	**Number of event statuses**	**Car Gearshift DR**	**Dummy TCU Gearshift DR**
POUS_PFDS	16	6.7	7.2

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.3. AT-9 dummy TCU Gearshift tip-in/kick down downshift

Tip-in downshift is the last measured kind of gearshift, which was driven with AT-9 and AVL DRIVE measurement was done. The problem with this gearshift is that the dummy TCU is not able to recreate the measurement correctly, so the DR for tip in downshift on the dummy TCU cannot be compared with car directly from measurement, because during one shift in car, there is a completely different shift happening on dummy TCU and this comparison makes no sense if they are not performing the same shift with nearly the same load and velocity. Figure 40 shows how far away the wished velocity and gears are from the dummy TCU. Main reason for this is the complexity of this shifts and that the dummy TCU is not yet developed in that way to perform this shift correctly.

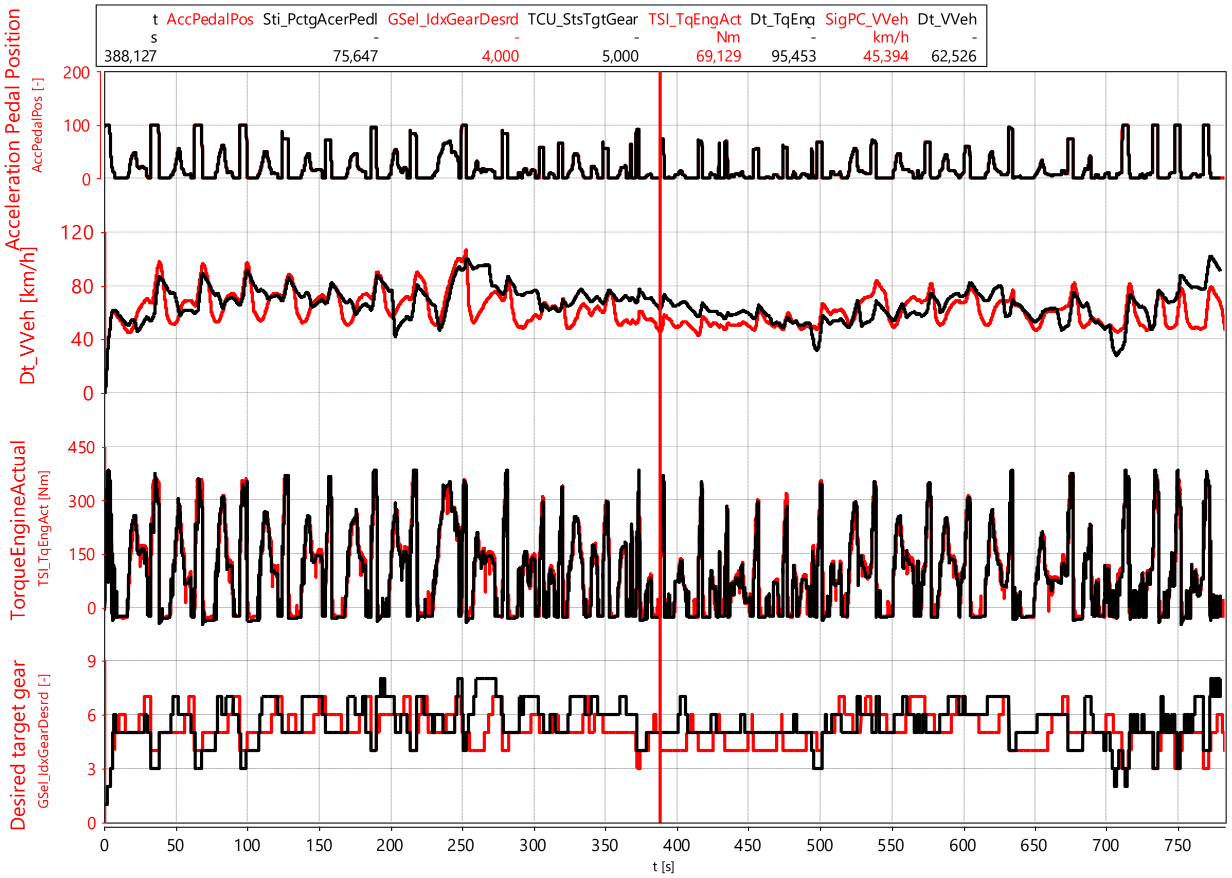


Figure 40 Dummy TCU Tip-in/kick down downshift

8.1.4. AT-9 HiL Gearshift Power on upshift

HiL DR is done with same maneuvers as dummy TCU here; the only problem with HiL is that the simulation was not done with the same SW version that car measurements, so small deviations in DR can be because of that, nevertheless, for comparing the DR different SW version is not that big of a factor as long as later all HiL measurements are done with the same SW status.

Like on dummy TCU, HiL Power on upshift was divided into 3 parts.

8.1.4.1. Low pedal positions

DR behavior on HiL is similar with dummy TCU where the DR is rising with higher gears. Gearshift 5 to 6 is here behaving differently with the big fall in DR compared to neighbored gearshifts. Main reason is engine speed behavior and acceleration, further explained in chapter 9.2

**Table 13 HiL DR in low pedal positions*

Gearshift	**Car DR**	**HiL DR**
1-2	7.4	6.4
2-3	7.5	7.6
3-4	7.2	6.0
4-5	6.8	7.8
5-6	7.2	6.2
6-7	7.6	8.3
overall	7.2	6.4

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.4.2. Mid pedal positions

DR in mid pedal positions seems pretty good, but this might be just a coincidence in this one case, because so good ratings at first try, compared to other results are unusual.

**Table 14 HiL DR in mid pedal positions*

Gearshift	Car DR	HiL DR
1-2	6.8	7.4
2-3	6.1	6.1
3-4	6.6	6.4
4-5	7.0	6.9
5-6	6.0	6.0
overall	6.3	6.3

8.1.4.3. High pedal positions

In higher pedal positions, the situation is back to the usual problem, with deviations in DR between low and high gears caused by engine speed and acceleration explained in chapter 9.2.

*Table 15 HiL DR in high pedal positions

Gearshift	Car DR	HiL DR
1-2	6.0	4.5
2-3	6.3	4.7
3-4	6.2	5.8
4-5	6.3	7.8
overall	6.2	4.9

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

8.1.5. AT-9 HiL Gearshift Coast/Brake on downshift

The overall DR over more cycles is like dummy TCU, again with 0.3 difference.

**Table 16 HiL DR Downshift*

Name of maneuver	**Number of event statuses**	**Car Gearshift DR**	**HiL Gearshift DR**
POUS_PFDS	16	6.7	7.0

When looking detailed into one cycle and comparing each gearshift, some bigger differences between DR occur, but the difference between gearshifts is constant between all of them, except the last one. The reasons for the differences and improvements will be discussed in chapter 9.2.

**Table 17 HiL one cycle DR downshift*

Gearshift	**Car DR**	**HiL DR**
7-6	7.8	8.9
6-5	8.1	9.1
5-4	7.8	7.6
4-3	6.4	7.4
3-2	7.7	7.1
overall	6.8	7.4

8.2.Summary

First simulations and results show that DR evaluation with AVL DRIVE can be done with dummy TCU or HiL and the results can provide realistically values, but there still have to be done some improvements to come nearer to the car values. The problems and improvements will be discussed in next chapters.

**Table 18 Comparing DR of measurement and simulations*

Gearshift	**Events**	**Car DR**	**HiL DR**	**Dummy TCU DR**
Power on Upshift	24	6.4	5.6	5.8
Power down Downshift	16	6.7	7.0	7.2

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

9. Evaluation of signal differences between car and simulations

In chapter 8 the evaluation is done purely on DR differences in different gears and does not give any answers how to solve the deviations or what is causing them. In this chapter I will look more detailed into some signals that may cause DR deviations and compare them. Focus is on velocity, acceleration, torque and engine speed signals.

9.1. Dummy TCU

9.1.1. Velocity deviation

Velocity deviation is one of the problems happening with simulation models. In dummy TCU with low pedal positions between velocities 20 km/h and 60 km/h, there happens velocity deviation between car and dummy TCU. This is causing the dummy TCU to shift earlier, but in general this is not affecting the DR in this case, because even though its shifting earlier, shifting is happening on same velocity and with torque and acceleration levels similar to the ones in higher gears where velocity deviation is not the case anymore. Main reason for this might be the resistances and that not all data is matching between car and simulation model which is leading to different calculations between simulation model and car. Regarding resistances, there are two main ways how resistance calculation are done in simulation models, one is with an polynomial $A*x^2 + B*x + C$ where coefficients A, B and C have to be estimated or with functions for rolling resistance, drag resistance and gravity. For my thesis I tried simulations with both estimations for resistances and in both cases the results in low velocity with low pedal positions are more or less the same. This leads to the conclusion that if there were not any other weather influences during the measurement that the resistance calculations are good and that the main reason for this deviation is coming from a potential data mismatch between car and simulation model. These mismatches can be caused by not having the same ratio in transmission or final drive. One additional cause for the problem might be some inside the car happening losses in low load level which are not considered by the simulation model. The velocity deviation can be clearly seen in Figure 41.

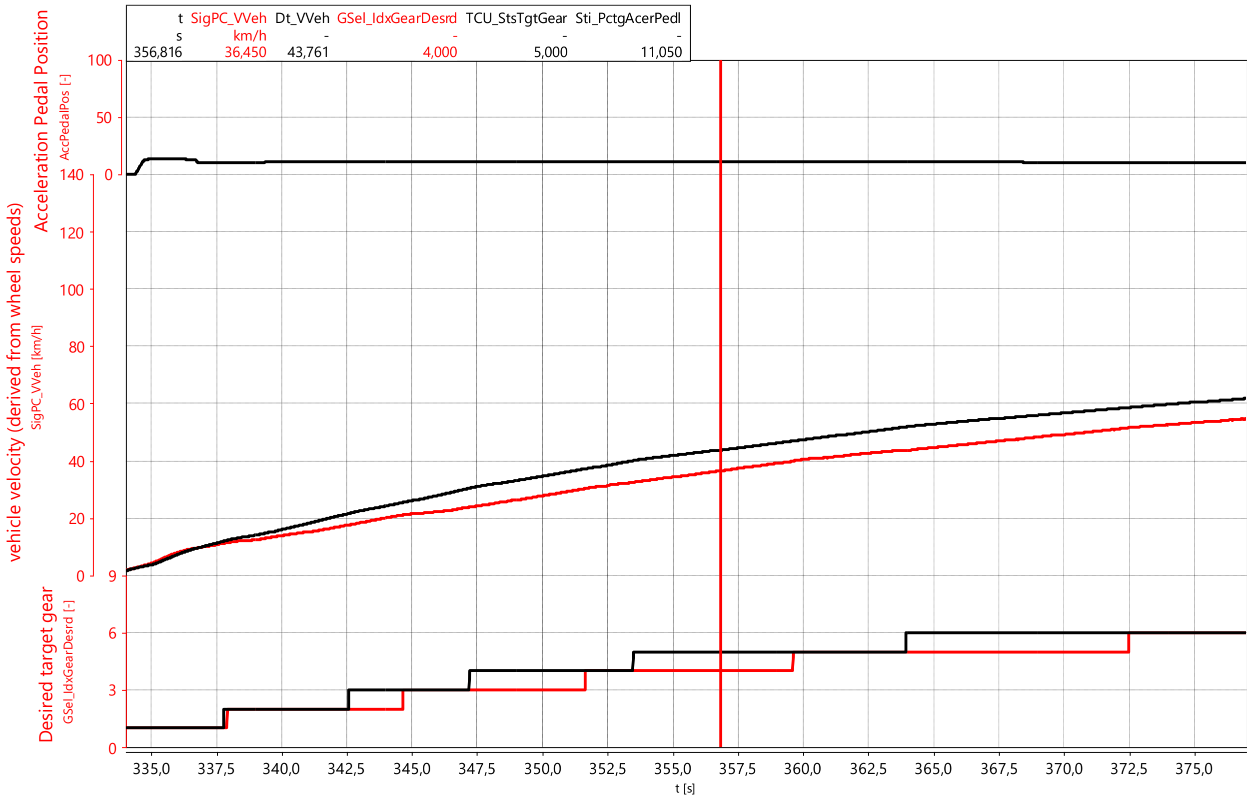


Figure 41 Dummy TCU low pedal position velocity deviation

With rising the pedal position, the velocity deviation is getting smaller and slowly not existing anymore.

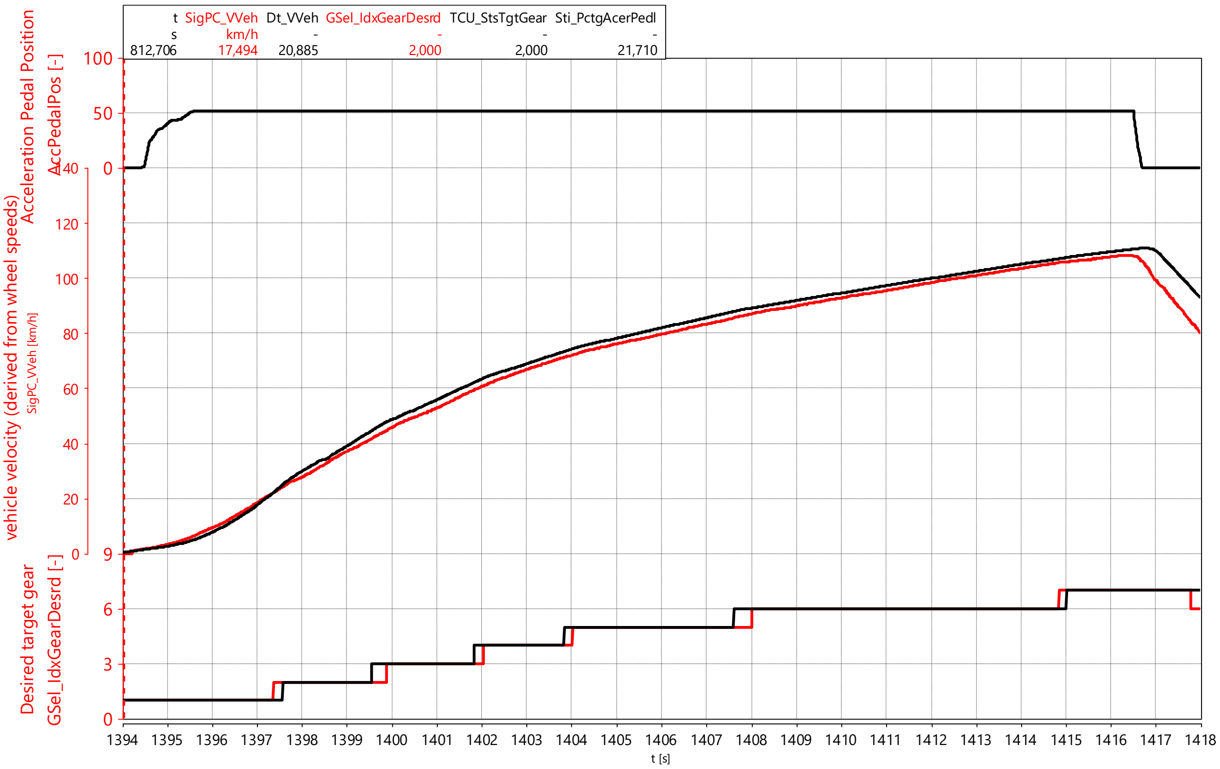


Figure 42 Dummy TCU Mid pedal position velocity deviation

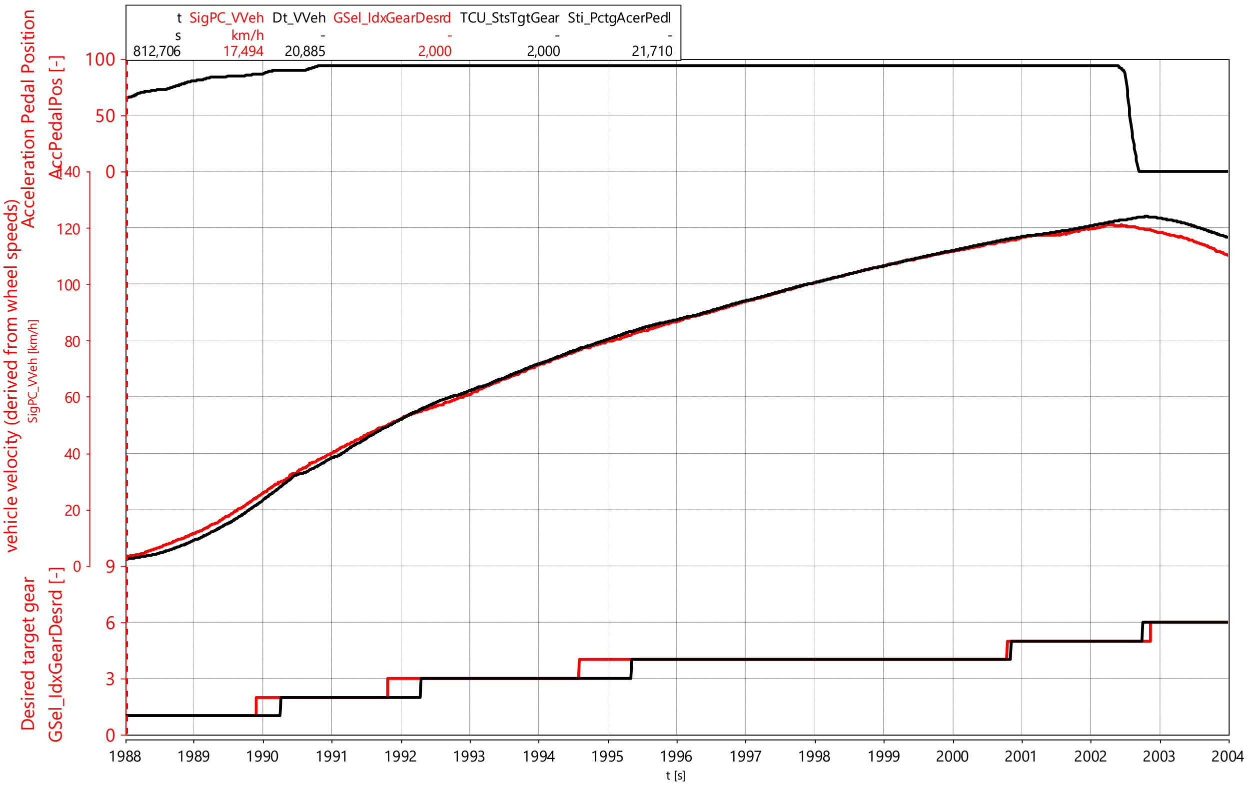
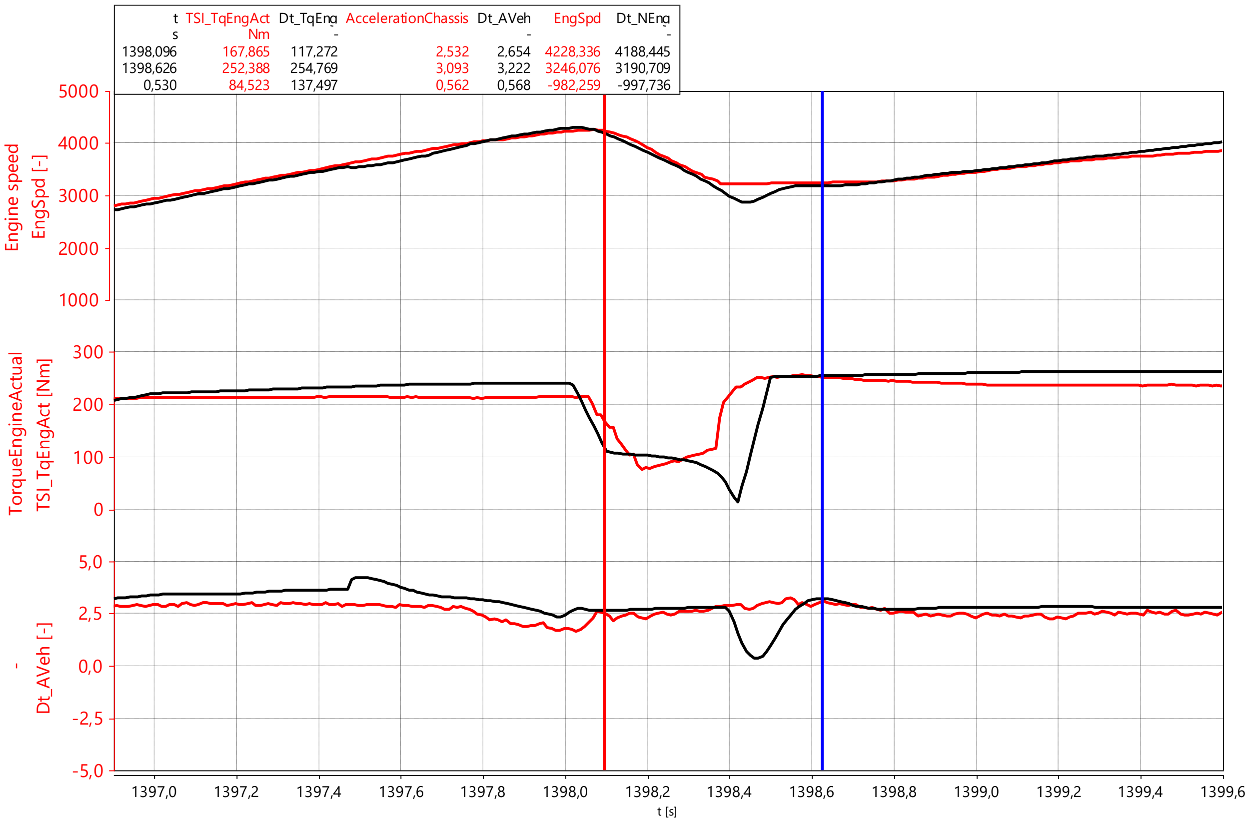


Figure 43 Dummy TCU High pedal position velocity deviation

9.1.2. Torque behavior during speed phase

As seen in chapter 7.2.1 the DR in low gears is much lower with dummy TCU then in the car-based evaluation. Main reason for this is that in these gears torque behavior during speed phase is causing big negative torque peak and is leading to unexpected acceleration behavior. Figure 44 shows this behavior during gearshift from 1st to 2nd gear with 50% pedal position.



t	TSI_TqEngAct	Dt_TqEng	AccelerationChassis	Dt_AVeh	EngSpd	Dt_NEng
s	Nm	-		-		-
1398,096	167,865	117,272	2,532	2,654	4228,336	4188,445
1398,626	252,388	254,769	3,093	3,222	3246,076	3190,709
0,530	84,523	137,497	0,562	0,568	-982,259	-997,736

Figure 44 Torque peak during speed phase

This torque peaks are getting smaller with higher gears and higher load, the same as the DR is getting better. So, the assumption that this is the main reason for bad DR in low gears is plausible. Figure 45 shows 4 different gearshifts, where its seen that higher the gear is, smaller the torque peak is, which leads then to higher, more accurate DR in higher gears. The solution for this problem is described in chapter 10.1

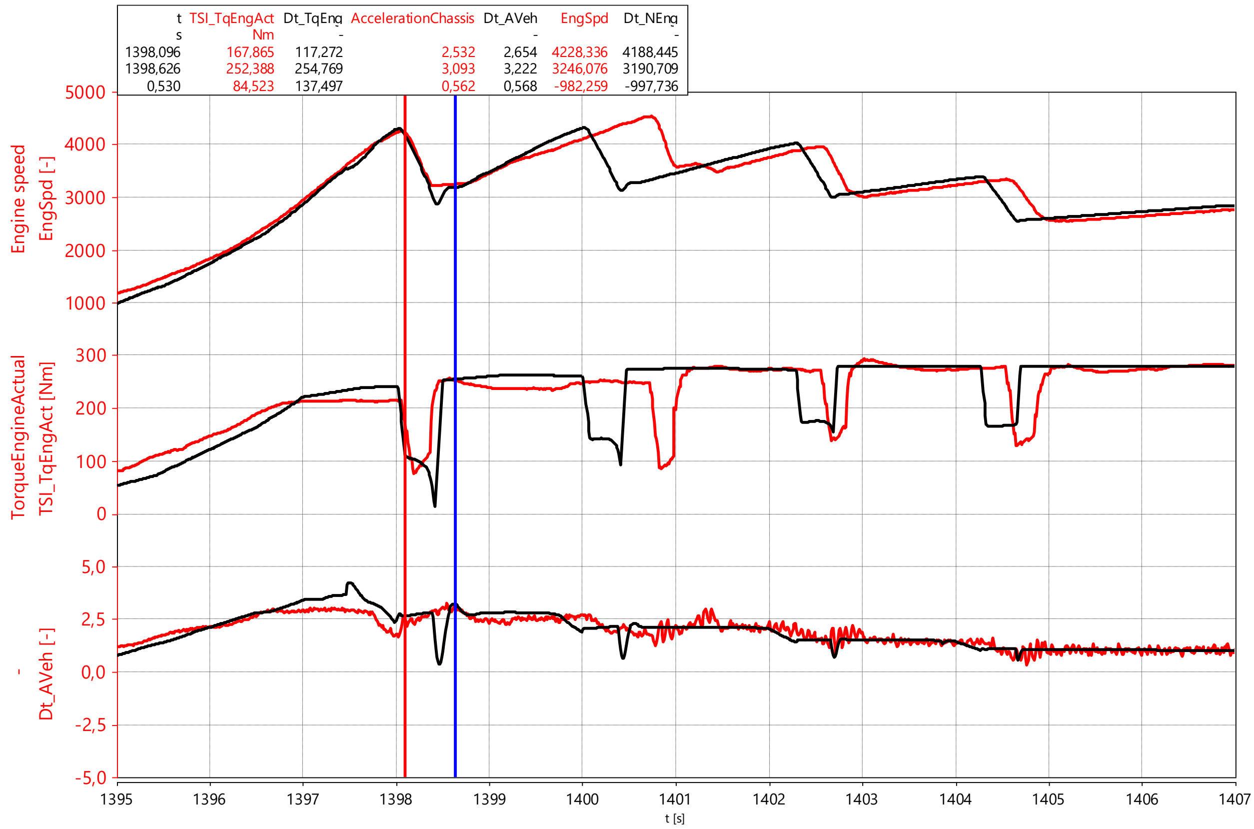


Figure 45 Torque peak during more gearshifts

9.1.3. Acceleration

In higher gears, where the torque behaviour is similar between car-measurements and dummy TCU, the DR is higher with dummy TCU. Reason for this is the acceleration signal. Acceleration in dummy TCU is much smoother than on car, where there is always some noise in the signal, which leads to DR deviations. The acceleration behaviour can be seen in Figure 46, with black for dummy TCU and red for car. Improvement solution is described in chapter 10.2.

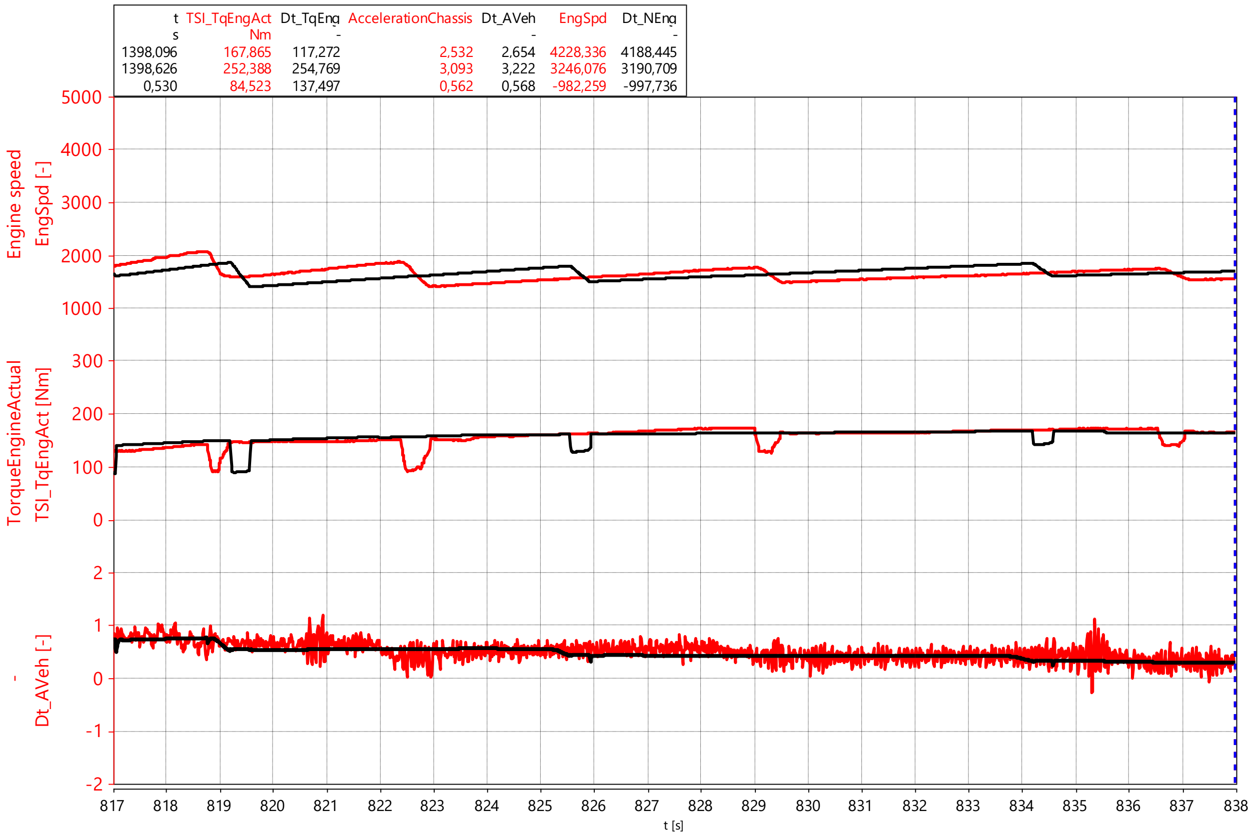


Figure 46 Dummy TCU acceleration in higher gears

9.2. HiL

9.2.1. Velocity deviation

Like the velocity deviation on dummy TCU, some deviation is also seen on HiL in lower pedal positions. The difference between velocities is a bit smaller than on dummy TCU. The reasons for this are explained in chapter 9.1.1.

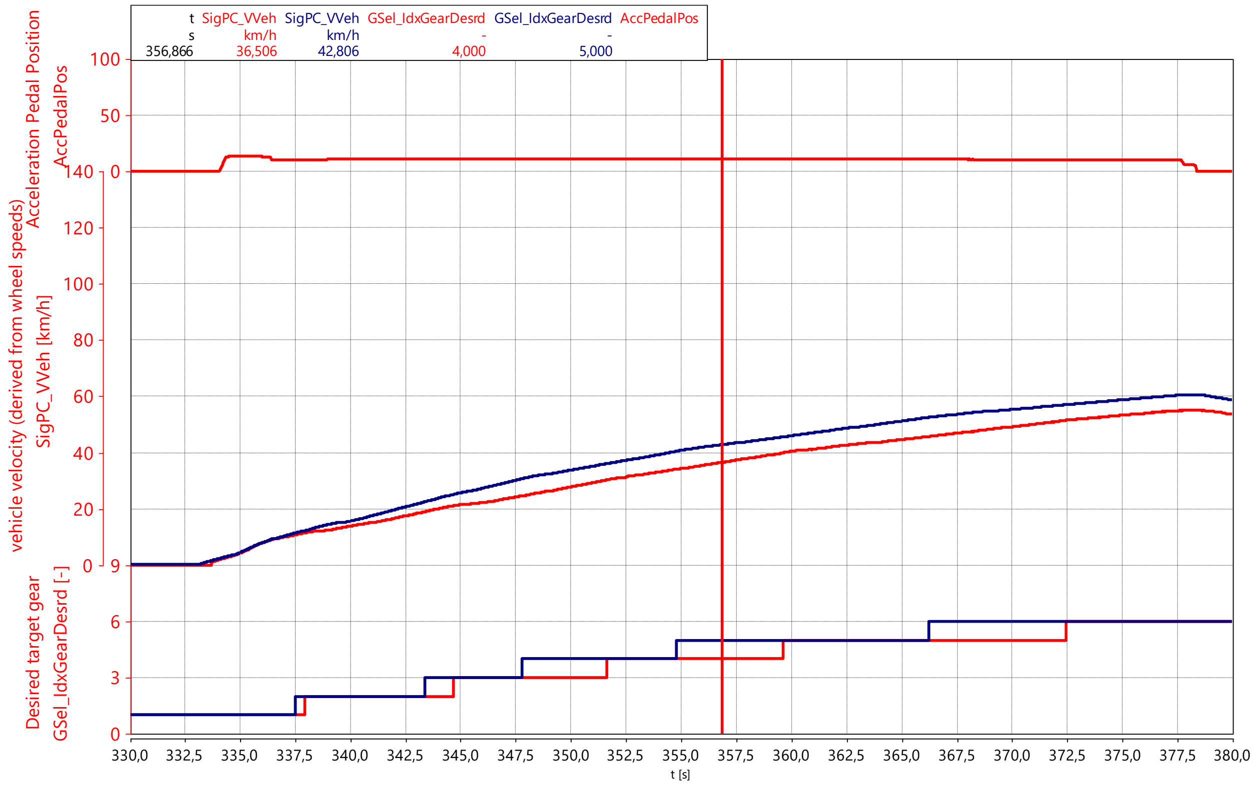


Figure 47 HiL low pedal velocity deviation

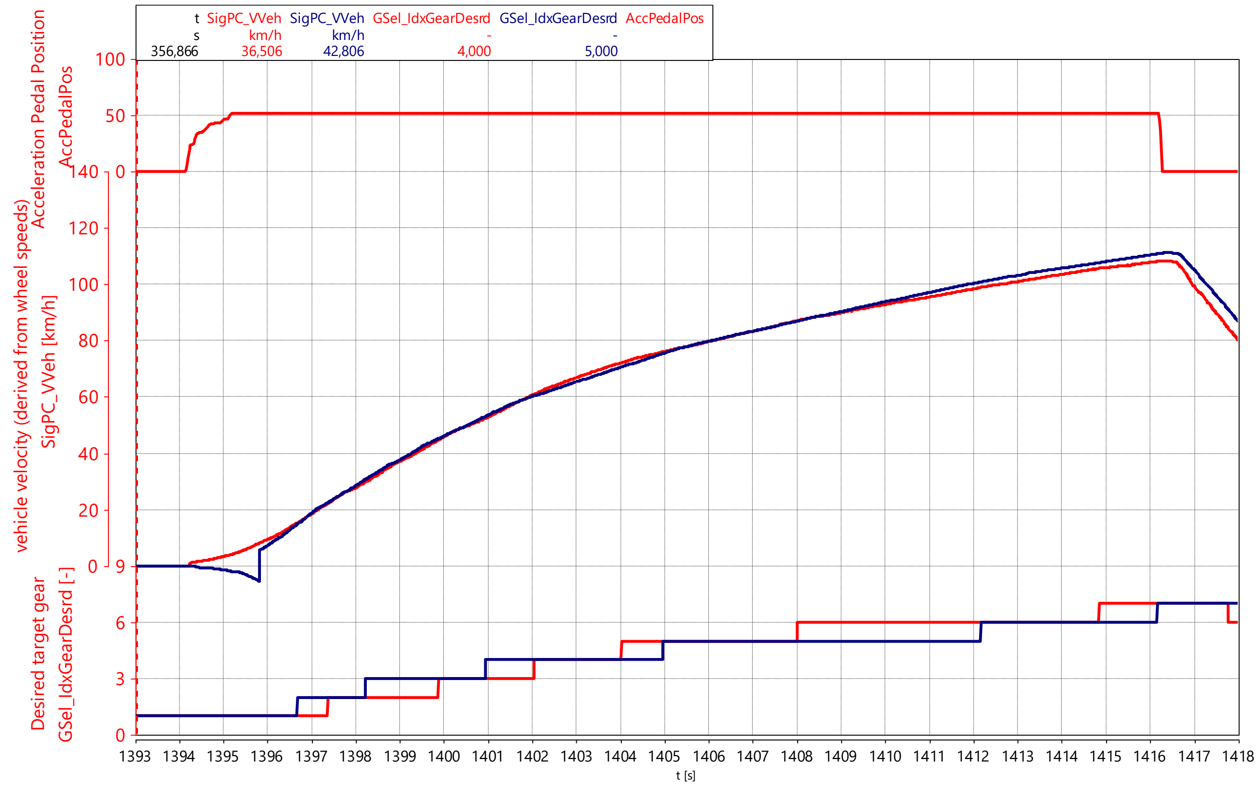


Figure 48 HiL mid pedal velocity deviation

9.2.2. Engine speed

Engine speed behaviour in some gearshifts is strange and has unexpected speed peaks during a shift. Figure 49 shows one upshift maneuver to 7th gear. The biggest engine speed miscalculation is seen on gearshift 5th to 6th gear. In this gearshift the DR difference is 1, with DR of 7.2 in car and 6.2 on HiL. For example, neighbored two shifts have a Higher DR on HiL then in car, so it is safe to assume that this engine speed peaks are causing a big DR deviation. Solution is provided in chapter 11.1.

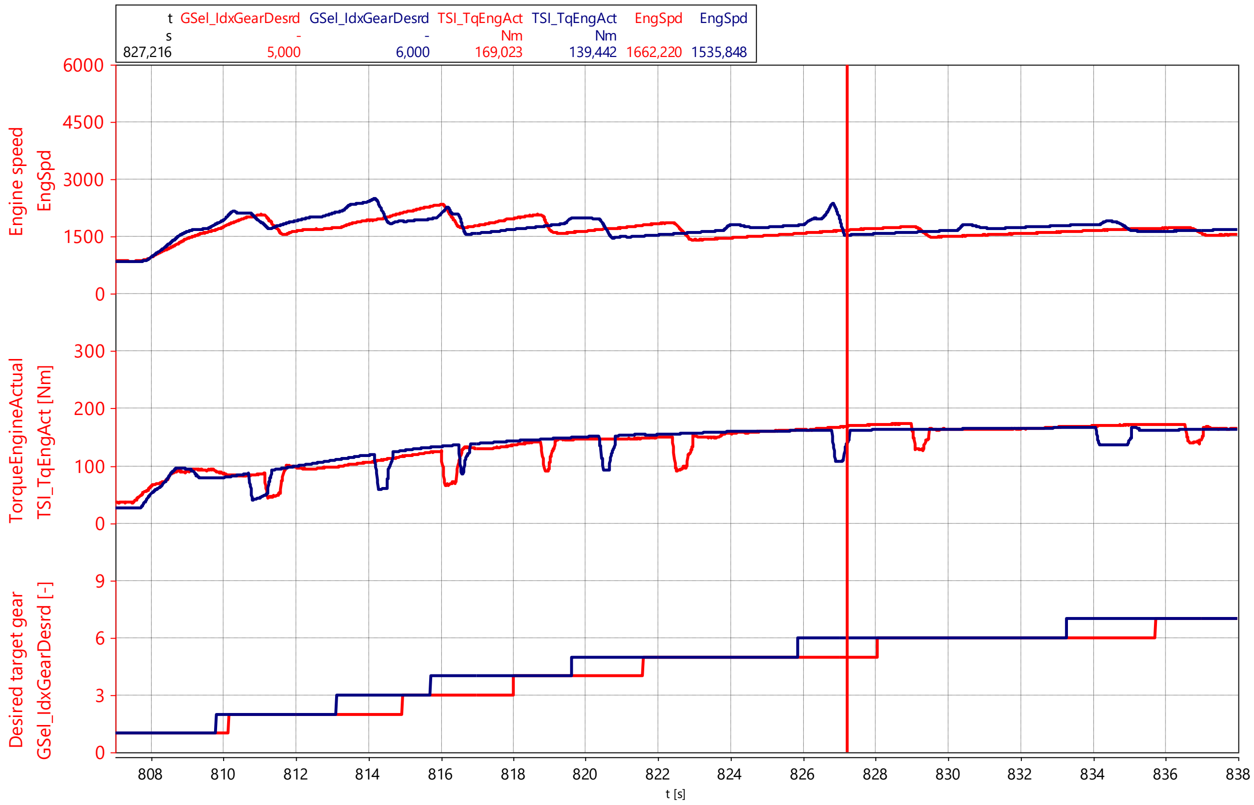


Figure 49 HiL engine speed

9.2.3. Acceleration

Like with the dummy TCU also on the HiL the missing noise behavior in higher gears might cause better DR then in car. In all gears, which have normal engine behavior the DR on the HiL is higher than in car. For HiL simulations same approaches for improving the acceleration calculation could be considered as in dummy TCU described in chapter 10.2

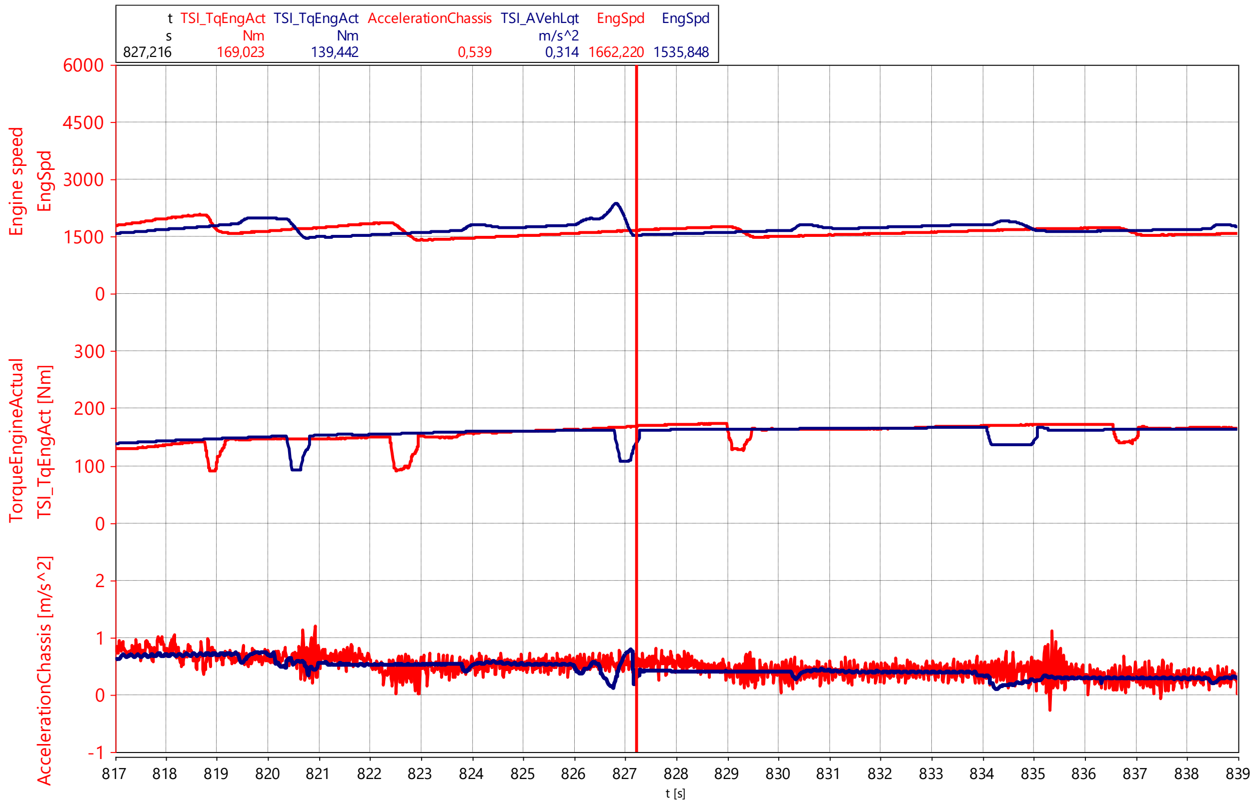


Figure 50 HiL acceleration

9.3. AVL DRIVE report

Additionally, to just measuring the DR, AVL DRIVE also provides the possibility to generate a report of the driven maneuvers, were it can exactly be seen which criteria is causing DR changes.

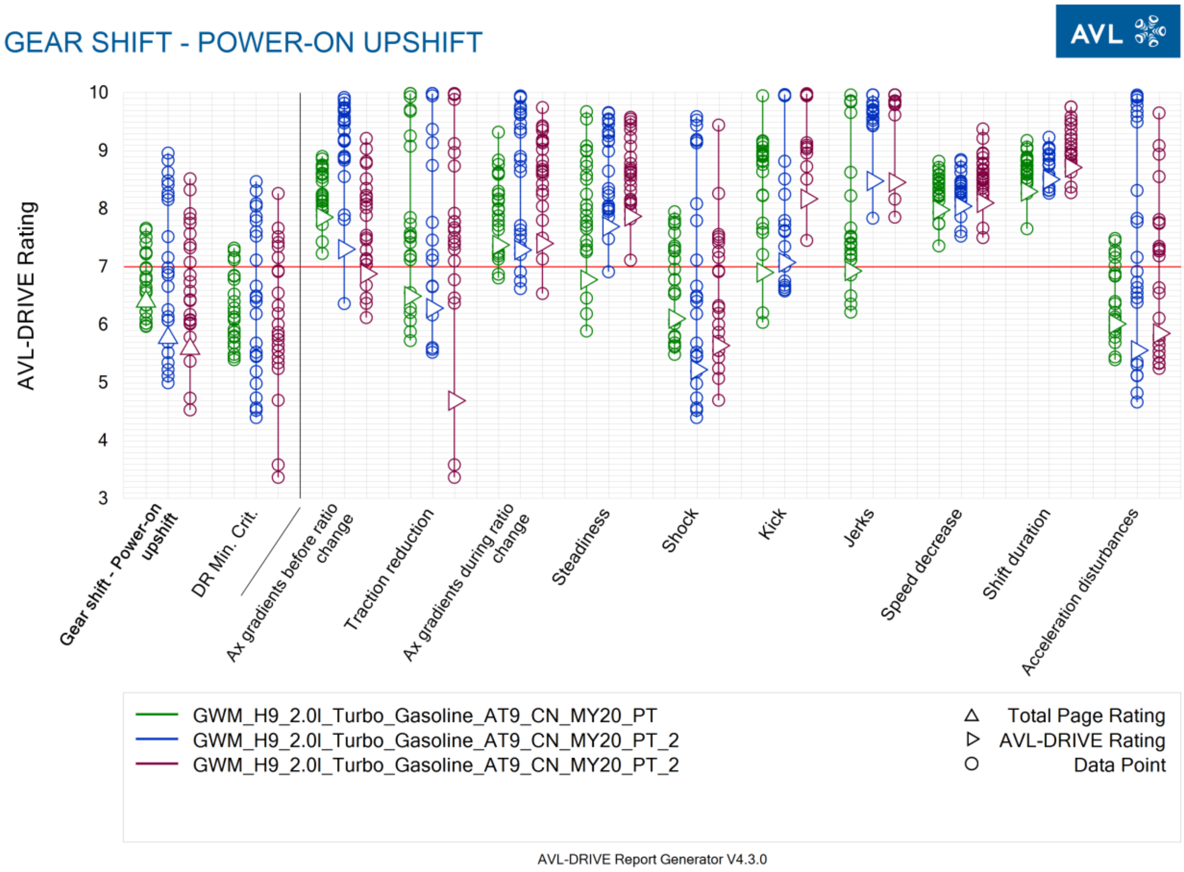


**Figure 51 AVL DRIVE report comparing real car, HiL and dummy TCU*

*Figure 51 shows in green how DR is evaluated over different criteria in car and in blue how it is in dummy TCU and violet for HiL. For Acceleration gradients during ratio change, speed decrease and shift duration can be said that they are matching good with car on HiL and dummy TCU. Acceleration gradients before ratio change, steadiness, shock, jerks and acceleration disturbances should be improved in both cases. Whereas Traction reduction and Kick is good with the dummy TCU and not on HiL.

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

*Table 19 *AVL DRIVE report comparing real car, HiL and dummy TCU*

Gearshift	**Events**	**Car DR**	**HiL DR**	**Dummy TCU DR**
Power on Upshift	24	6.4	5.6	5.8
Acceleration gradients before ratio change	24	7.9	6.9	7.3
Traction reduction	24	6.5	4.7	6.3
Acceleration gradients before during change	24	7.4	7.4	7.3
Steadiness	24	6.8	7.9	7.7
Shock	24	6.1	5.6	5.2
Kick	24	6.9	8.2	7.1
Jerks	24	6.9	8.5	8.5
Speed decrease	24	8.0	8.1	8.0
Shift duration	24	8.3	8.7	8.5
Acceleration disturbances	24	6.0	5.9	5.6

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

10. Dummy TCU adjustments

10.1. Torque behaviour

As described in chapter 8.1.1.2, the main problem in the dummy TCU with DR in lower gears is the unexpected torque peak in the speed phase of torque handover. In this speed phase the goal of the TCU is to bring engine speed from one level to another with torque intervention. In case of upshift, engine speed has to drop, in downshift it needs to rise. Torque intervention can be achieved in two ways. One way is via engine and the other is with clutch. In the dummy TCU all of this has to be modelled better to avoid any miscalculation.

Current model for speed phase is firstly calculating the gradient at which engine speed is dropping and from this calculation it is choosing how much engine torque intervention the gearshift needs and how much clutch torque intervention. And here in this decision is the error in the current dummy TCU. It gives us out how the best way to split the torque intervention would be, but it is not considering if the engine is even capable of doing that much torque intervention that is required. And in low gearshifts the engine cannot deliver as much as it is required so in the end of the speed phase there is not enough torque intervention to complete the gearshift correctly, which is causing the model having this big negative torque peak at the end of the shift phase, so that shifting can happen.

The idea to get rid of these peaks in low shifts is, to calculate the torque intervention like the intervention in the real TCU. This means that after the calculation of speed gradient and dividing the torque intervention in engine and clutch part an additional check is implemented. This check will proof if the engine can provide required torque or not. If not, it will provide the maximum amount of what can be provided, and the rest will be added to clutch.

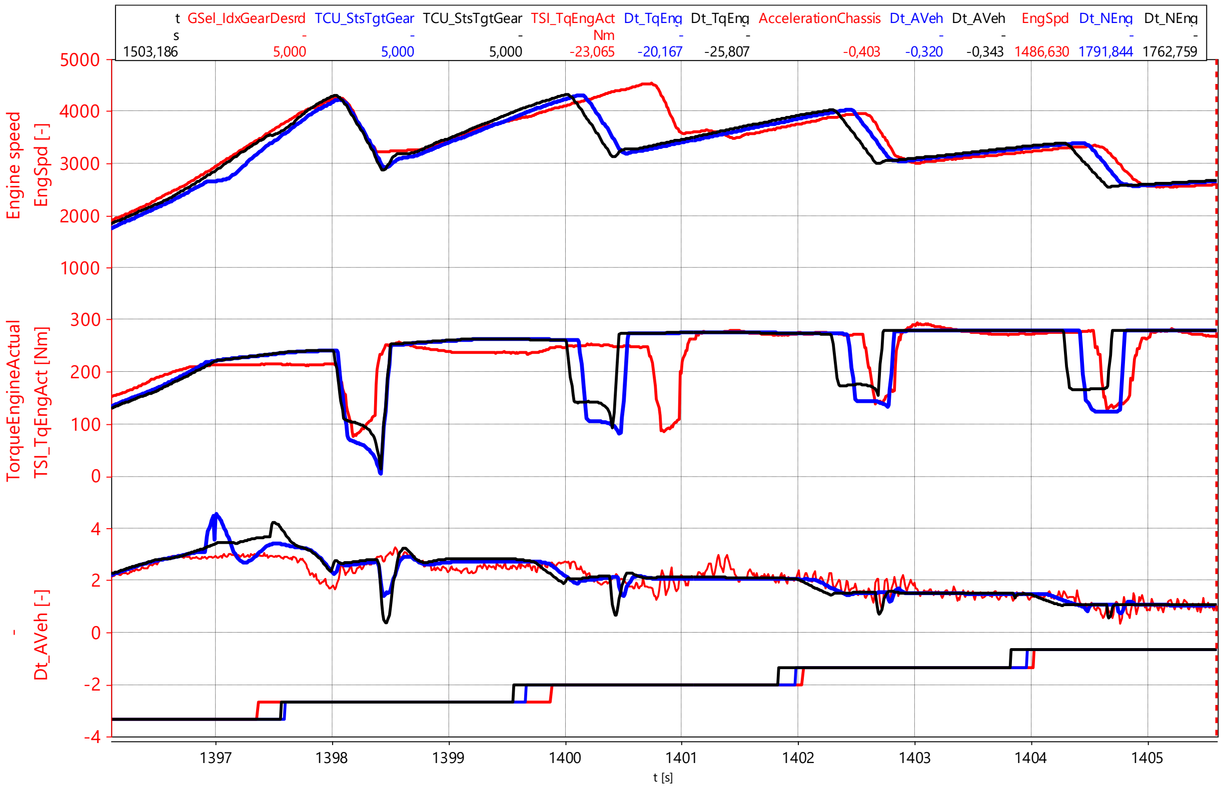


Figure 52 Dummy TCU behavior after model change

Figure 52 shows with blue line how much torque and acceleration behavior has improved with this model change and therefore also DR has to be way better. Torque peaks are still occurring but in lower values, which means that acceleration behavior after torque intervention is much better.

10.1.1. Power on Upshift

10.1.1.1. Low pedal position

*Table 20 New dummy TCU model DR in low pedal positions

Gearshift	**Car DR**	**Old Dummy TCU DR**	**New Dummy TCU DR**
1-2	7.4	6.1	8.0
2-3	7.5	6.1	7.5
3-4	7.2	8.2	8.0
4-5	6.8	8.8	8.3
5-6	7.2	8.5	8.7
6-7	7.6	8.2	8.4
overall	7.2	6.5	7.9

10.1.1.2. Mid pedal position

**Table 21 New Dummy TCU model DR in mid pedal positions*

Gearshift	**Car DR**	**Old Dummy TCU DR**	**New Dummy TCU DR**
1-2	6.8	5.0	5.5
2-3	6.1	5.2	6.4
3-4	6.6	6.3	7.8
4-5	7.0	7.5	7.5
5-6	6.0	8.3	8.3
6-7	7.4	8.1	8.2
overall	6.4	5.5	6.1

10.1.1.3. High pedal position

**Table 22 New Dummy TCU model DR in high pedal positions*

Gearshift	**Car DR**	**Old Dummy TCU DR**	**New Dummy TCU DR**
1-2	6.0	5.5	6.4
2-3	6.3	5.7	6.5
3-4	6.2	6.7	7.4
4-5	6.3	6.9	7.5
overall	6.2	5.8	6.6

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

10.1.2. Downshift

**Table 23 New dummy TCU model DR for Downshift*

Name of maneuver	Number of event statuses	Car Gearshift DR	Old Dummy TCU Gearshift DR	New Dummy TCU Gearshift DR
POUS_PFDS	16	6.7	7.2	7.5

10.1.3. Conclusion

Torque intervention improvement is achieving exactly what the goal was. With better modeling of torque intervention, torque and acceleration peaks get smaller and following this the DR in lower gears improves. The intervention is still not perfect, but we know now where the problem was and how to improve it even more if necessary.

10.2. Acceleration

The main problem with acceleration is the missing noise behavior seen in Figure 46. Modeling the acceleration noise can be very complex, because it has to consider different vehicle influenced aspects, as for example, road interferences, vehicle load, suspension model. Diving into these aspects and figuring out what is causing when noise into acceleration is exceeding the work of this thesis. In my thesis the goal was just to implement a noise into the model, calibrate it properly so that the level of noise is somehow similar to car acceleration, and compare the DR with this noise, if it is causing any DR change.

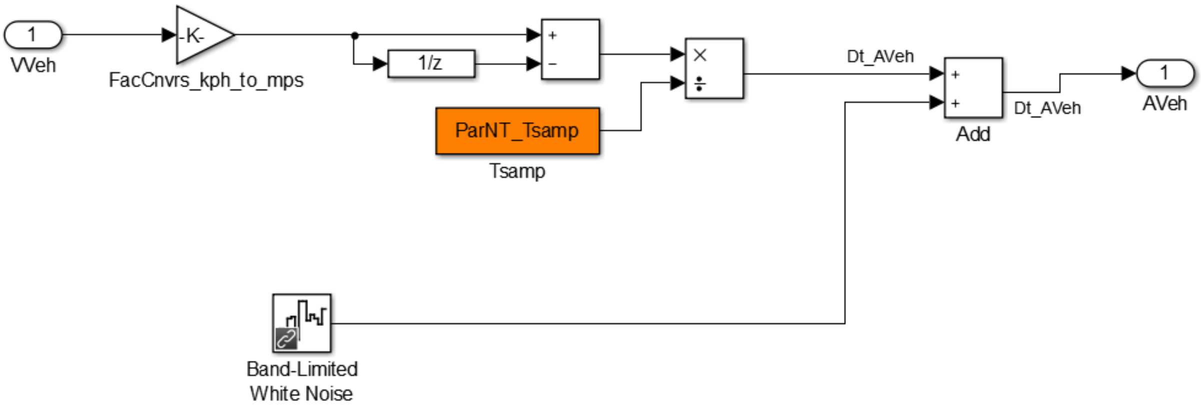


Figure 53 White noise added to acceleration

With this addition the acceleration is now much noisier and more like the vehicle acceleration seen in Figure 54. With blue the car acceleration is seen and with pink the new simulation acceleration. On the cursor can be seen that now at one point both accelerations are around 2 m/s^2.

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

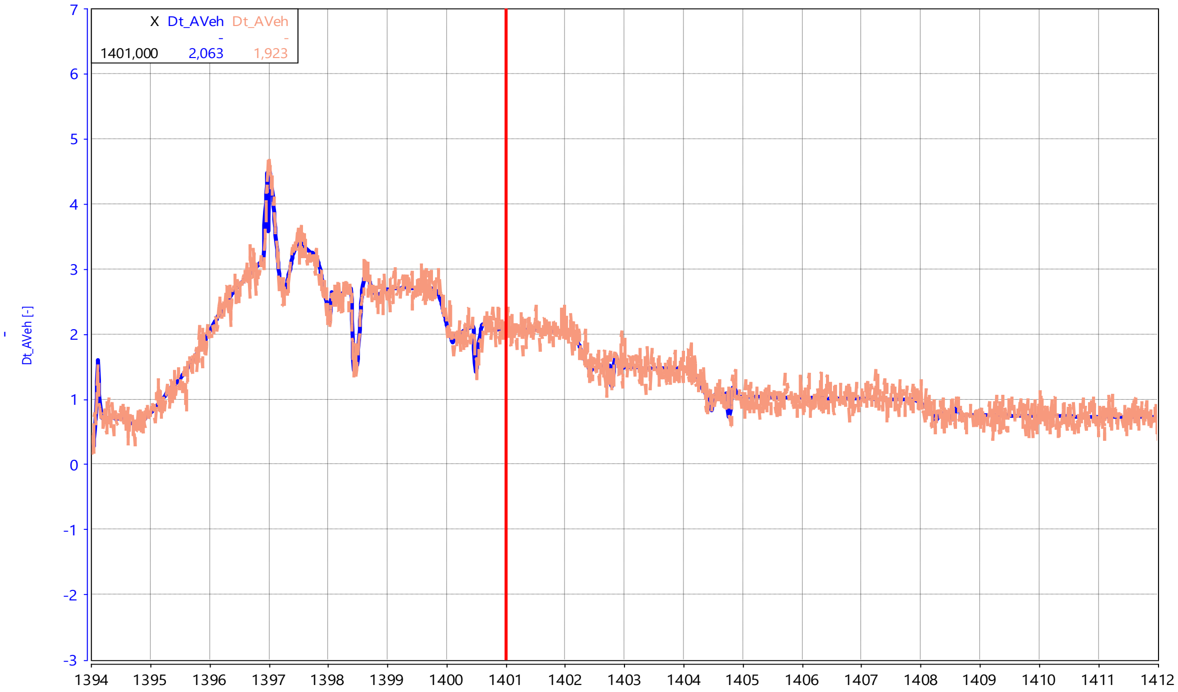


Figure 54 Acceleration with white noise

10.2.1. Power on Upshift

10.2.1.1. Low pedal position

**Table 24 DR with new acceleration with low pedal position*

Gearshift	Car DR	Dummy TCU old acceleration DR	Dummy TCU new acceleration DR
1-2	7.4	8.0	7.6
2-3	7.5	7.5	7.3
3-4	7.2	8.0	7.2
4-5	6.8	8.3	6.9
5-6	7.2	8.7	7.3
6-7	7.6	8.4	7.7
overall	7.2	7.9	7.2

10.2.1.2. Mid pedal position

**Table 25 DR with new acceleration with mid pedal position*

Gearshift	Car DR	Dummy TCU old acceleration DR	Dummy TCU new acceleration DR
1-2	6.8	5.5	5.6
2-3	6.1	6.4	6.7
3-4	6.6	7.8	7.3
4-5	7.0	7.5	6.9
5-6	6.0	8.3	7.3
6-7	7.4	8.2	7.4
overall	6.4	6.1	6.2

10.2.1.3. High pedal position

**Table 26 DR with new acceleration with high pedal position*

Gearshift	Car DR	Dummy TCU old acceleration DR	Dummy TCU new acceleration DR
1-2	6.0	6.4	6.6
2-3	6.3	6.5	6.4
3-4	6.2	7.4	7.2
4-5	6.3	7.5	7.4
overall	6.2	6.6	6.6

**AVL DR evaluation was done with initial Software where no Calibration or Functional tests were done yet, so lower DR values were expected.*

10.2.2. Downshift

**Table 27 DR with new acceleration for downshift*

Name of maneuver	Number of event statuses	Car DR	Dummy TCU old acceleration DR	Dummy TCU new acceleration DR
POUS_PFDS	16	6.7	7.5	6.5

10.2.3. Conclusion

Adding noise to acceleration is getting the DR of the dummy TCU in higher gears nearer to car DR. So, acceleration noise has a huge impact to DR evaluation in higher gears. Until now this noise is just a Simulink block, but for future improvements of the model would be nice to simulate this noise more realistically, with some suspension system and virtually added interferences.

10.3. Summary

Overall can be said that this model change is improving the DR a lot and for DR calculation the dummy TCU is modeled very good. On upshift and downshift simulations, torque and acceleration behavior are improved and can be compared with torque and acceleration measured in the real car setup. The same goes also for the AVL DRIVE report, where the criteria are now closer between car and dummy TCU, just steadiness gave with the old model better results, all other criteria improved. What is missing now is for future projects to model acceleration noise better and consider all the aspects causing the noise.

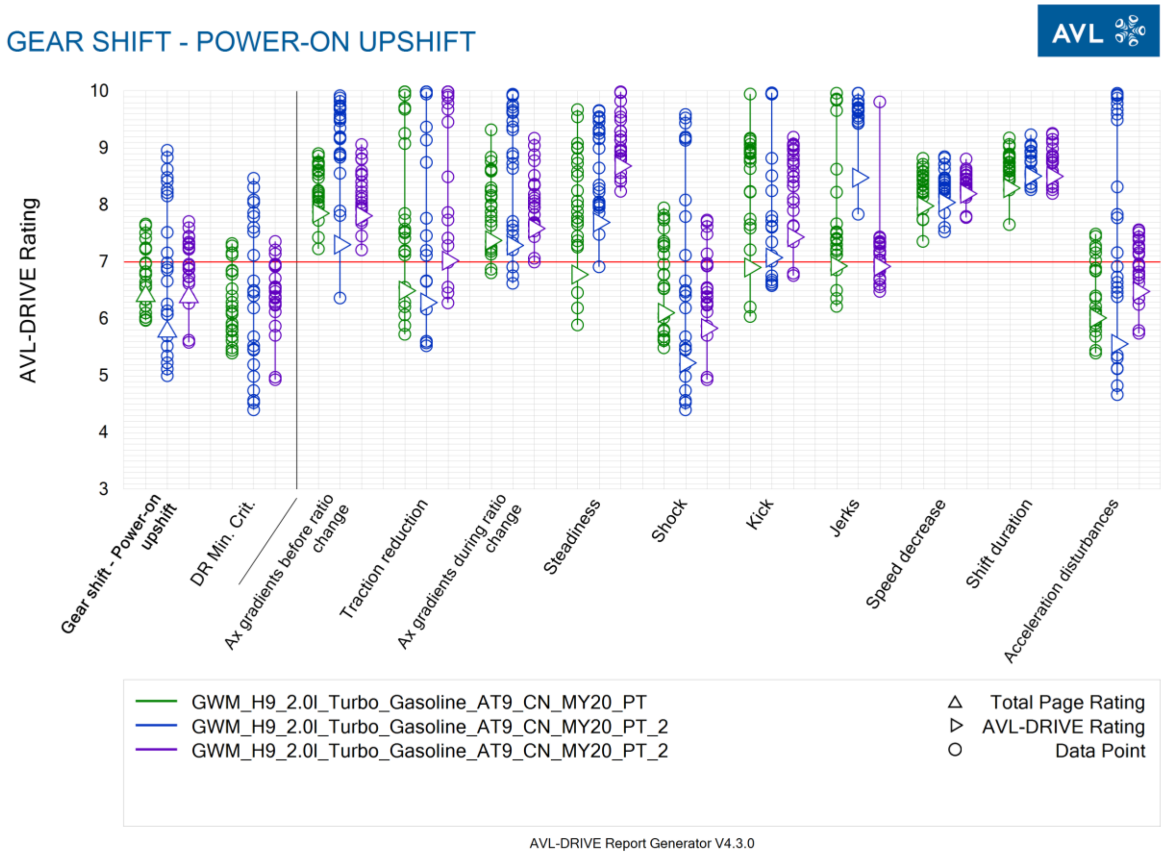


******Figure 55 AVL DRIVE report for improved dummy TCU simulation*

**Table 28 AVL DRIVE report for improved dummy TCU simulation*

Gearshift	**Events**	**Car DR**	**New dummy TCU DR**	**Old dummy TCU DR**
Power on Upshift	24	6.4	6.4	5.8
Acceleration gradients before ratio change	24	7.9	7.8	7.3
Traction reduction	24	6.5	7.0	6.3
Acceleration gradients before during change	24	7.4	7.6	7.3
Steadiness	24	6.8	8.7	7.7
Shock	24	6.1	5.8	5.2
Kick	24	6.9	7.4	7.1
Jerks	24	6.9	6.9	8.5
Speed decrease	24	8.0	8.2	8.0
Shift duration	24	8.3	8.5	8.5
Acceleration disturbances	24	6.0	6.5	5.6

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

11. HiL adjustments

11.1. Engine speed

Engine speed problem is coming because the incoming clutch is either filling to slow, to fast or because of clutch kiss point is to early or too late.

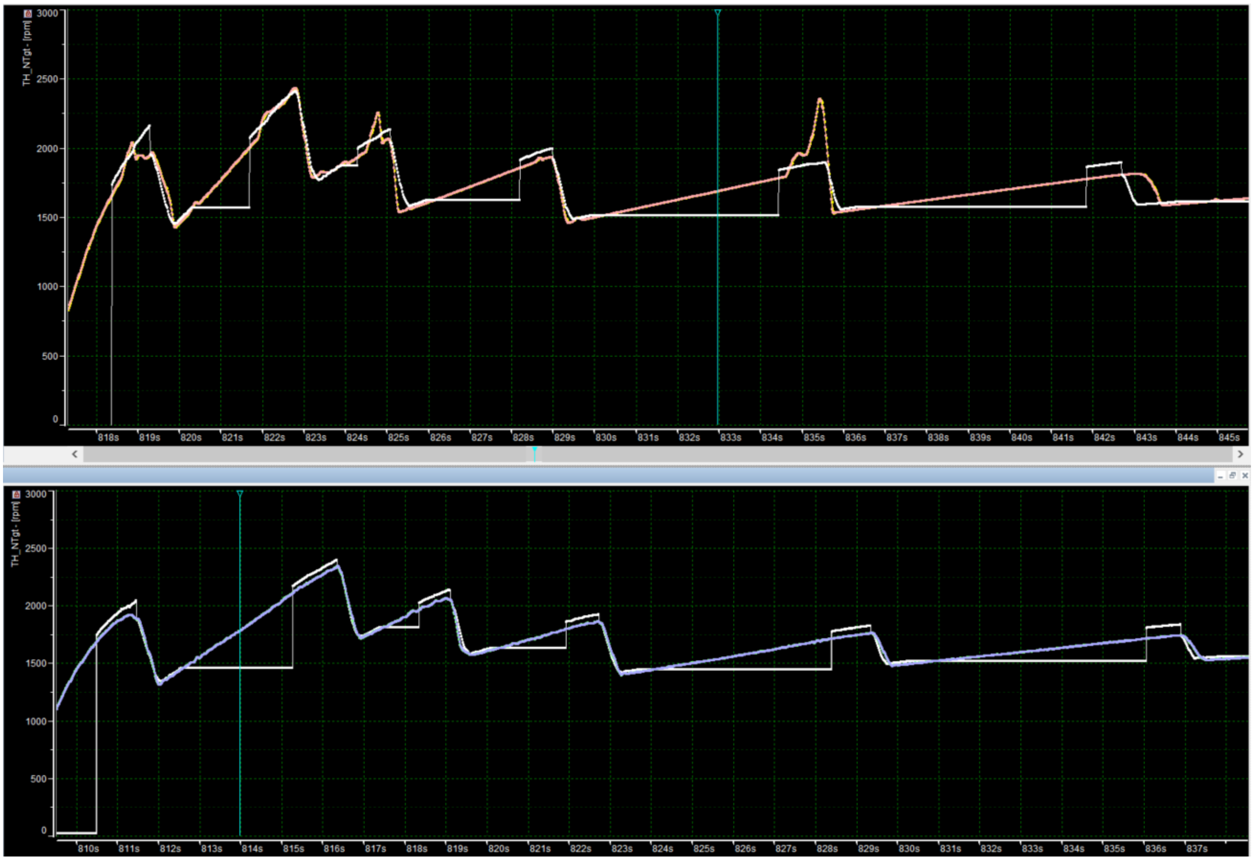


**Figure 56 HiL engine speed error*

*Figure 56 shows in upper image in white the desired engine speed during gearshift and in orange the actual speed. Lower image is the same data just from car measurements. To get the engine speed to the correct level in each gearshift, every clutch must be calibrated correctly. From maneuver in *Figure 56 it is seen that gearshifts 2nd to 3rd and 4th to 5th look good, so the incoming clutches are calibrated fine for these two gearshifts all other shifts need some improvement.

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

11.1.1. Clutch calibration

11.1.1.1. Clutch filling

Clutch model for filling the clutches is now modeled simple, without any hydraulic model. The model is getting from the TCU the current which is converted with maps to clutch pressure and this clutch pressure is in the next step converted to volume flow as seen in Figure 57. Each clutch has his own calibration at which levels and how the conversion from pressure to flow happens and this calibration is now not correct for all clutches, which causes the engine speed peaks.

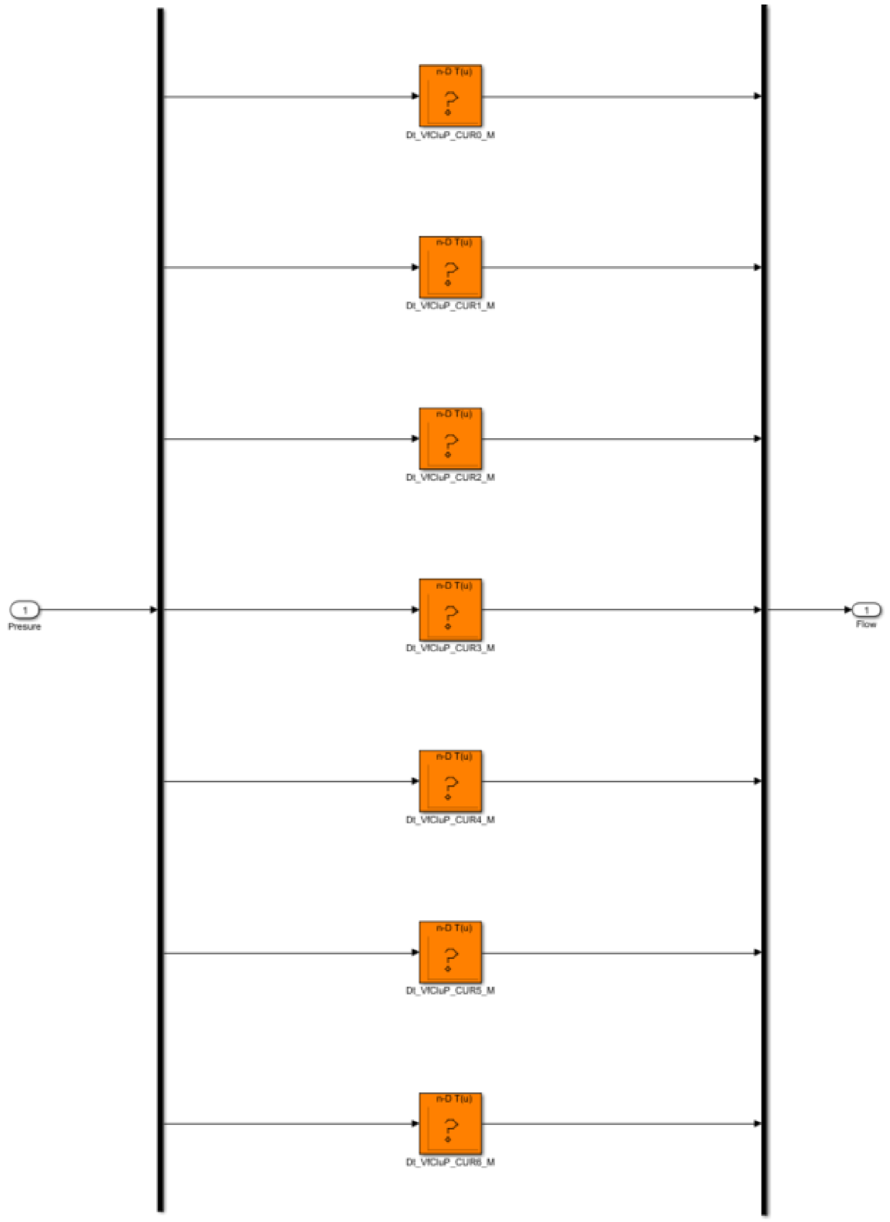


Figure 57 Clutch filling

For calibration of clutch filling it is important to know if the clutch is filling to fast or to slow. In cases shown in *Figure 56, gearshift 1st to 2nd gear is an example of too fast filling and gearshifts 3rd to 4th and 5th to 6th of too slow filling. In cases where the filling is to fast the volume flow values must be smaller, so that the clutch will take more time to reach the target value where kiss point is reached and the wished profile for engine speed can be followed. Same logic applies also for gearshifts where the filling is too fast, just that in these cases the volume flow values have to be reduced. It has to be considered that some clutches are incoming in more than just one gearshift, so it is important to look at both gearshifts when values for one clutch are changed not that in the end one gearshift will look better and the other worse.

11.1.2. Engine speed after calibration

Because this model is simplified there is no actual data how the calibration has to be done for each clutch, so it is always just manual checking to get the proper calibration values. After trying various possible values for conversion pressure to volume flow, values which result in better engine speed during gearshift have been developed. The problem is that these values deliver now good engine speed behavior with a specific load, as seen in Figure 58. But these changes are not considering now how the engine speed is behaving with a different load different pressure values, which can lead to have now worse results in some cases. Solution for this would be to implement in future a model which has different clutch calibration for different vehicle loads and not always the same calibration.

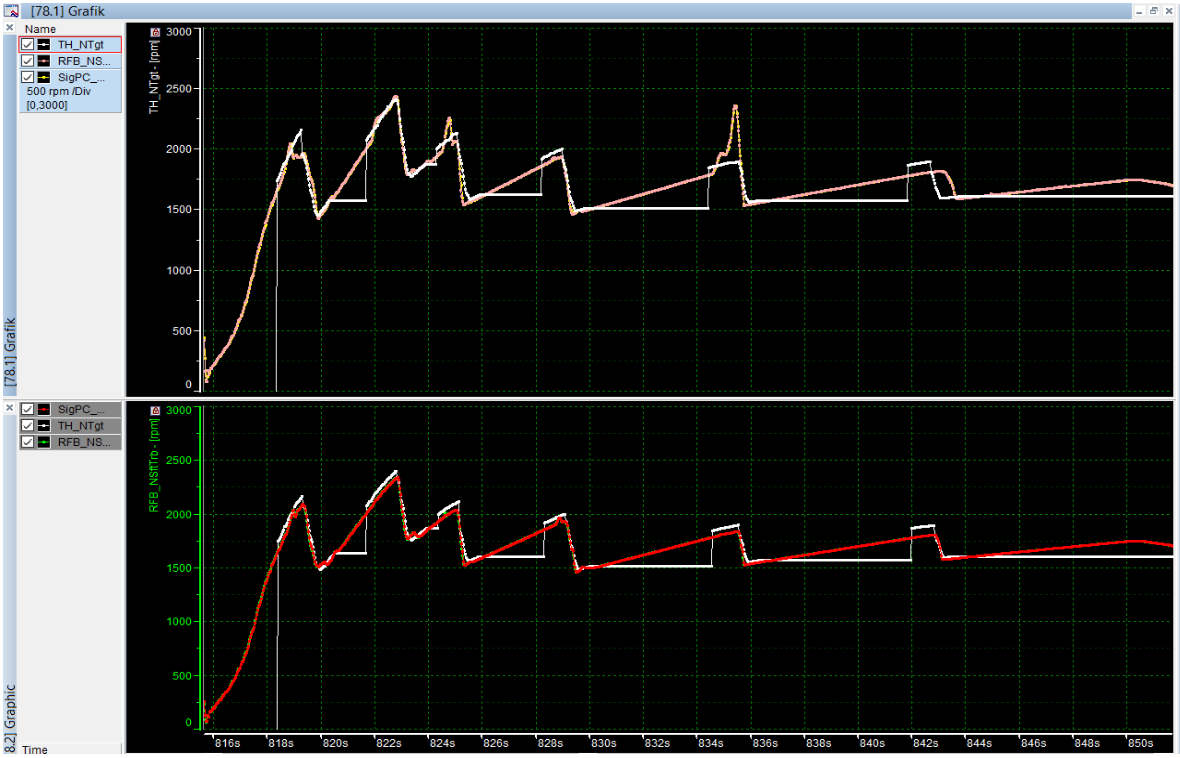


*Figure 58 Engine speed after calibration

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

11.1.3. DR after engine speed calibration

11.1.3.1. Low pedal position

**Table 29 Low pedal position DR with new calibration*

Gearshift	Car DR	Old HiL DR	New HiL DR
1-2	7.4	6.4	6.8
2-3	7.5	7.6	7.1
3-4	7.2	6.0	5.9
4-5	6.8	7.8	7.8
5-6	7.2	6.2	7.1
6-7	7.6	8.3	8.4
overall	7.2	6.4	6.5

11.1.3.2. Mid pedal position

**Table 30 Mid pedal position DR with new calibration*

Gearshift	Car DR	Old HiL DR	New HiL
1-2	6.8	7.4	5.9
2-3	6.1	6.1	5.4
3-4	6.6	6.4	5.2
4-5	7.0	6.9	6.6
5-6	6.0	6.0	6.5
overall	6.3	6.3	5.6

** AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

11.1.3.3. High Pedal positions

**Table 31 High pedal position DR with new calibration*

Gearshift	Car DR	Old HiL DR	New HiL DR
1-2	6.0	4.5	5.5
2-3	6.3	4.7	5.5
3-4	6.2	5.8	5.6
4-5	6.3	7.8	6.9
overall	6.2	4.9	5.6

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

11.1.4. Summary

In conclusion about engine speed calibration it can be said, that engine speed does have a big influence in DR evaluation, so proper engine speed curves deliver better DR. Main problem is that until now, the clutch is calibrated the same for all pedal positions, which leads to the fact that even with calibrating the clutches, there are still cases where old calibration was better, seen in *Table 30. Here, the overall DR is now worse than before and also some gearshifts in *Table 29 and *Table 31 were better before, but the overall DR was improved. DRIVE report delivers similar conclusion as already the DR. Overall the DR is better, but not all criteria are now better than before. Solution to improve engine speed in different pedal positions would be to model the calibration so that the calibration would consider more maps for one clutch in different pedal positions and not just one map for all positions like it is now, or to implement a completely new model for clutch filling.

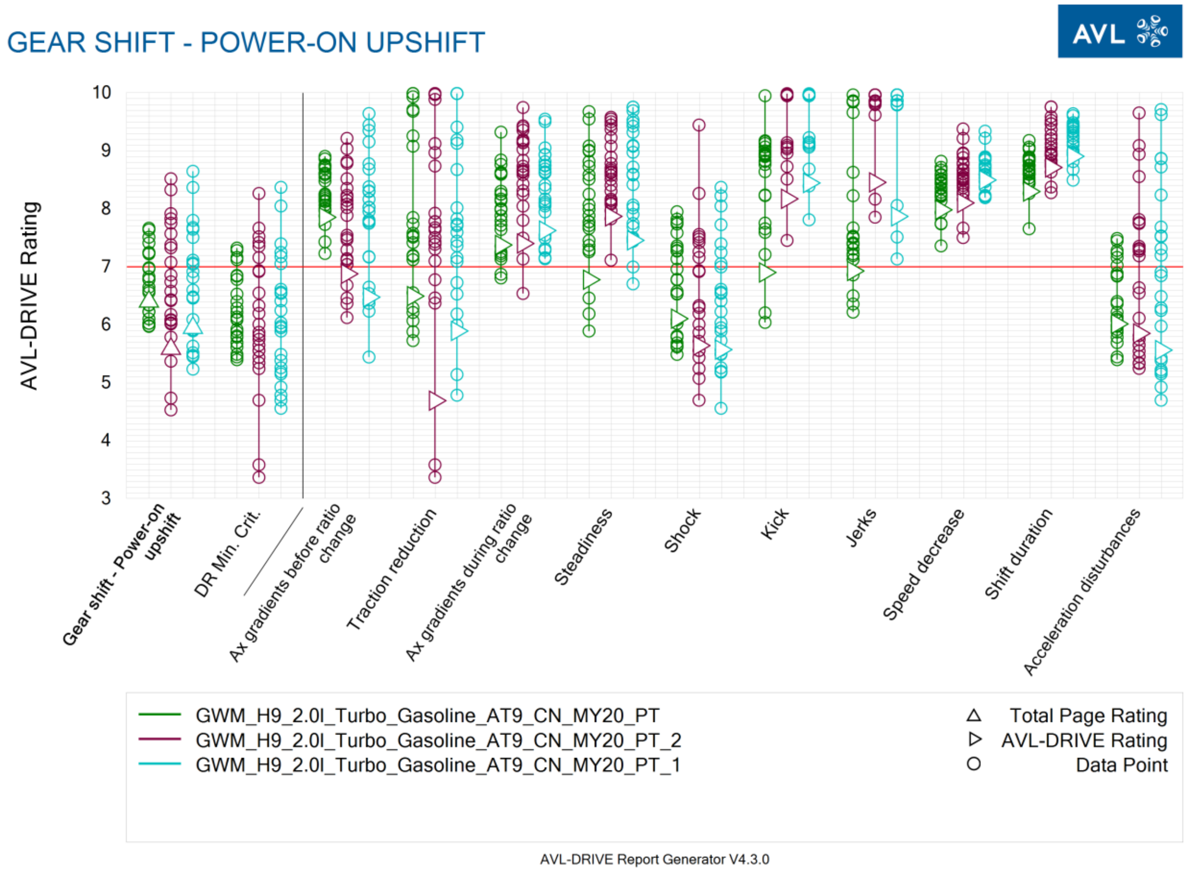


**Figure 59 AVL DRIVE report for improved HiL simulation*

Table 32 AVL DRIVE report for improved HiL simulation

Gearshift	**Events**	**Car DR**	**New HiL DR**	**Old HiL DR**
Power on Upshift	24	6.4	5.9	5.6
Acceleration gradients before ratio change	24	7.9	6.5	6.9
Traction reduction	24	6.5	5.9	4.7
Acceleration gradients before during change	24	7.4	7.6	7.4
Steadiness	24	6.8	7.5	7.9
Shock	24	6.1	5.6	5.6
Kick	24	6.9	8.4	8.2
Jerks	24	6.9	7.9	8.5
Speed decrease	24	8.0	8.5	8.1
Shift duration	24	8.3	8.9	8.7
Acceleration disturbances	24	6.0	5.6	5.9

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

12. Testcases

For future projects, manoeuvres which follow the given accelerator pedal position make no sense, because DR evaluation on HiL or dummy TCU has to be done before Car tests, so given pedal positions will not be available. Therefore, testcases have to be created so that all of these manoeuvres can be driven before getting real vehicle test data. In HiL the testcases are created with ECU test and for dummy TCU, the testcases are done in Simulink with a stateflow, the testcases include all manoeuvres from chapter 5.3.

12.1. Simulink testcases

All Simulink testcases are saved and written inside one stateflow as it can be seen in Figure 60. The constant IdxTestCase choses then which testcases will be driven.

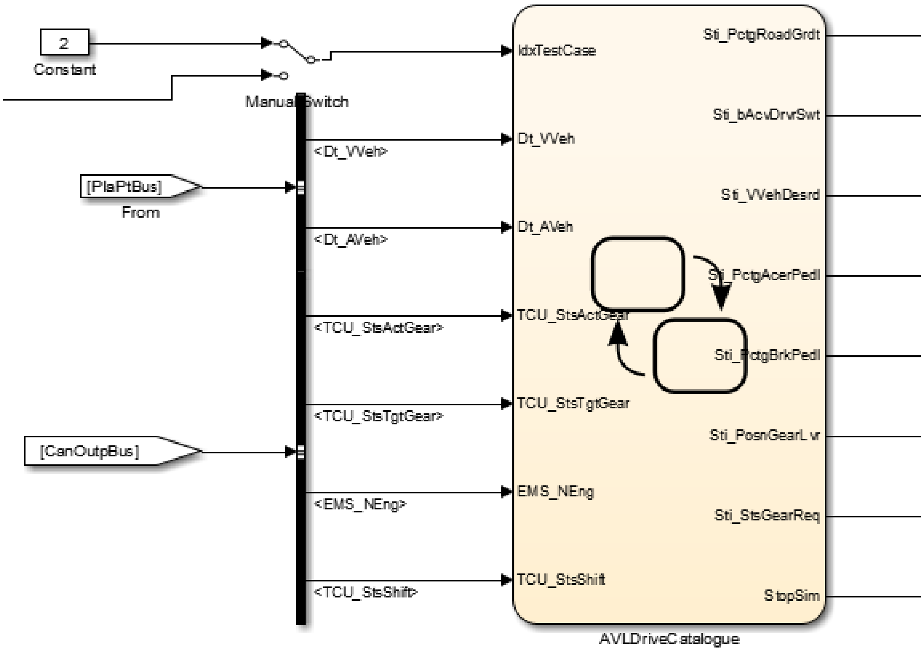


Figure 60 Simulink AVL Drive catalogue

Main inputs for the test cases are vehicle acceleration and velocity engine speed, target gear and actual gear, the important outputs for external driver model are accelerator pedal position, brake pedal position and gear lever position.

All testcases are built in a similar way, where conditions from AVL Drive catalogue are being implemented inside a statechart.

12.1.1. Power on Upshift

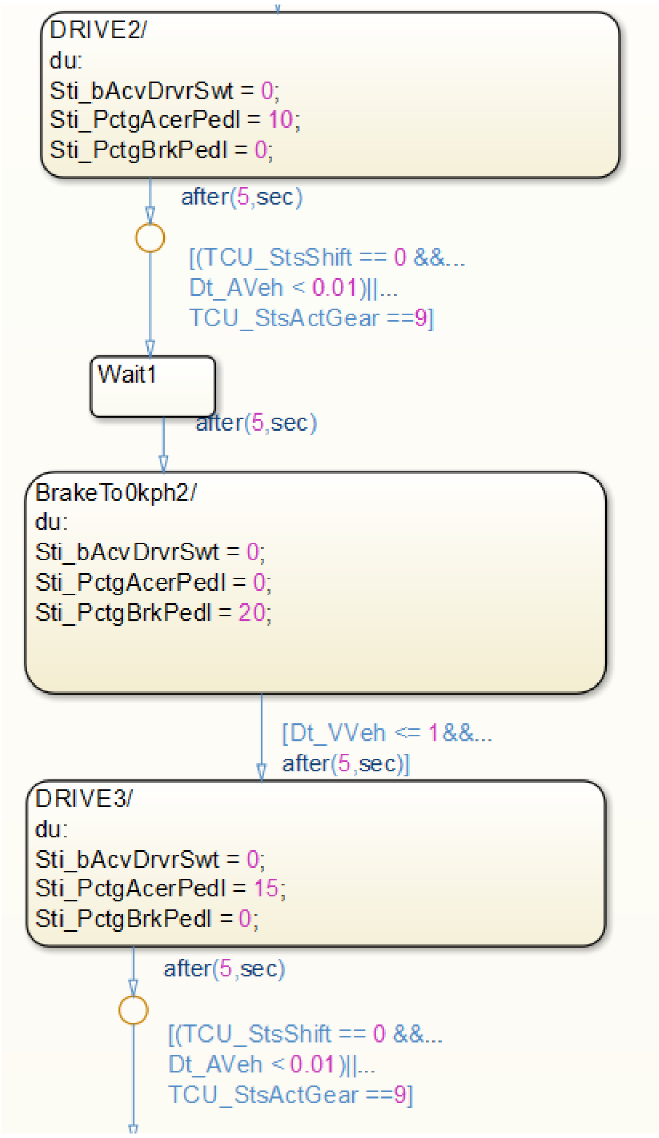


Figure 61 Simulink testcase Power on Upshift

Figure 61 is showing one part of Simulink testcase Power on Upshift. The conditions are the same as they are described in chapter 5.3.1. At defined pedal position the model should accelerate until highest gear is reached or model is not accelerating anymore, after one of this condition is fulfilled, the vehicle should brake down to standstill and the repeat with next pedal position. This condition in fulfilled 12 times during this testcase, for each required pedal position.

12.1.2. Tip out Upshift quick

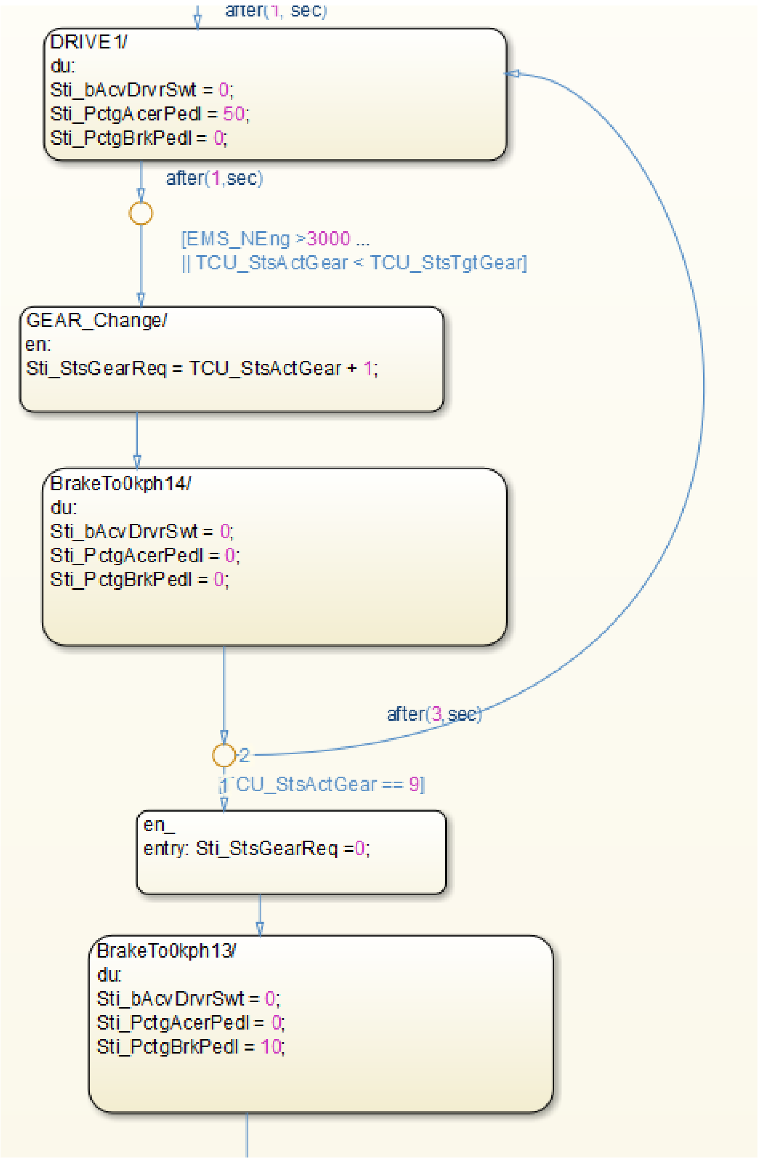


Figure 62 Simulink testcase Tip out Upshift quick

For this testcase the Vehicle should accelerate at 50% or 100% pedal position until defined engine speed is reached, or shift request signal is triggered. The problem with this testcase with the dummy TCU is, that after reaching the defined engine speed, shift request is not triggered, and Vehicle is not shifting automatically. Therefore, I implemented a Trigger block, which is after reaching the desired engine speed triggering the Shift request signal, so that the Vehicle is shifting. After the shift request is done and accelerator pedal is on 0%, the driver is waiting 3 seconds to shift and then is repeating the whole procedure until 9th gear is reached

12.1.3. Tip out Upshift slow

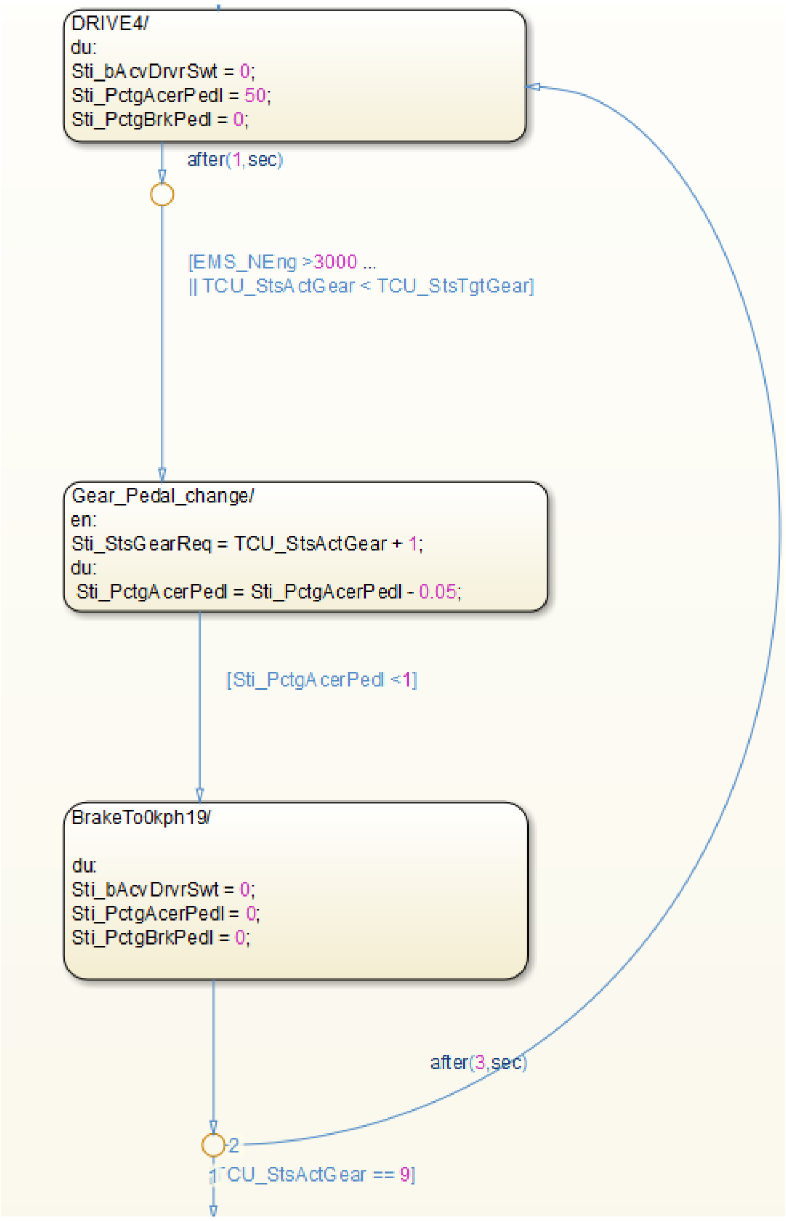


Figure 63 Simulink testcase Tip out Upshift slow

This testcase is very similar to the previous one, the only difference is that after triggering the shift request, also the pedal designment must be modeled. Normally the Simulink driver is disengaging the pedal immediately, for this testcase it is needed to take 1 second. For this to happen in 1 second, every time step, some part of the pedal must be disengaged. If I have 1000 steps per second, I need to model it so that for 50% pedal position, 0,05% of the pedal has to be disengaged per step.

12.1.4. Coast/brake downshift

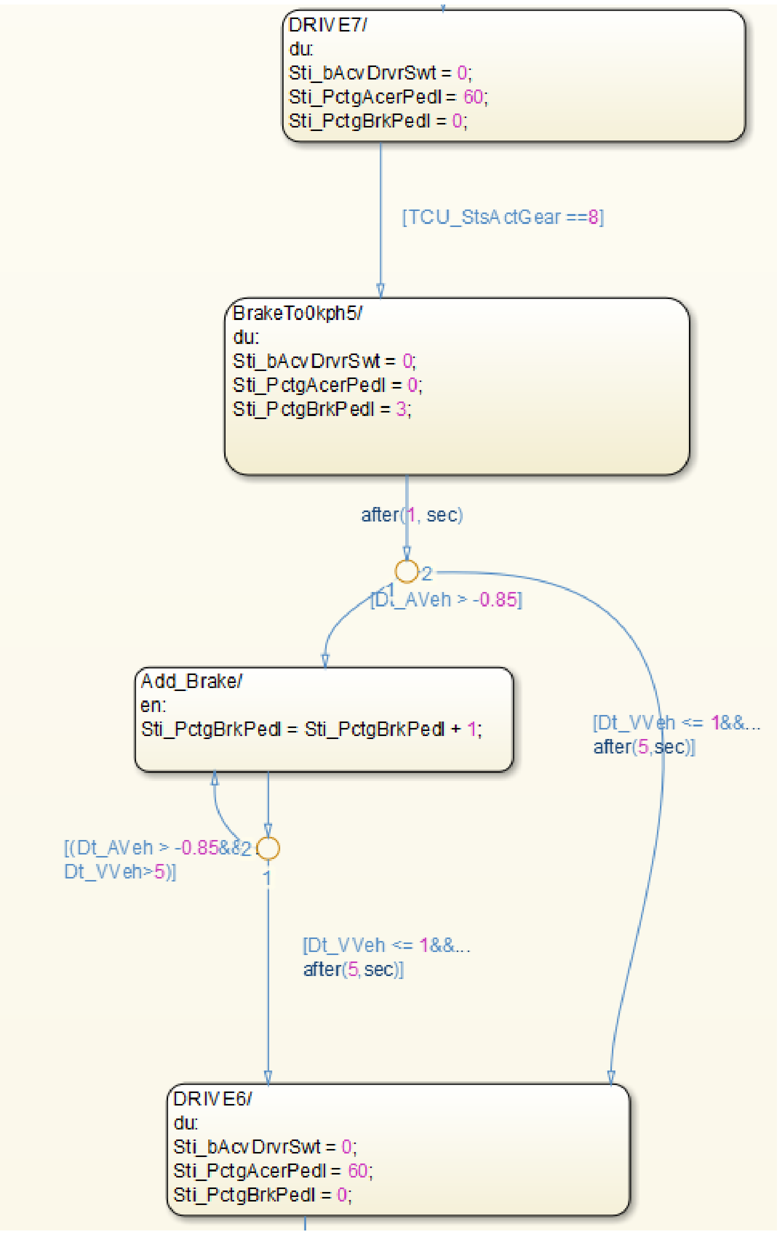


Figure 64 Simulink testcase Coast/Brake Downshift

For the downshift testcase, the Vehicle has to accelerate until last possible gear is reached. After reaching the defined gear, the brake phase is starting. At first the Vehicle is braking with a defined Value until the deceleration is lower as allowed, when the deceleration is hitting the lowest possible value, brake pedal value is increasing by 1. This procedure is looping over the testcase, until the Vehicle is not moving anymore. If I take as example the scenario in **Error! Reference source not found.**Figure 64, the Vehicle is braking with 3% brake pedal, until the deceleration is lower than -0.85 m/s^2, when this value is reached, the brake pedal value is increasing to 4% and so on until standstill. This procedure is then repeated with all 4 required cases of deceleration.

12.1.5. AVL DR

12.1.5.1. Power on Upshift

Table 33 Power on Upshift dummy TCU

Number of events	DR
76	6.6

12.1.5.2. Coast/brake Downshift

Table 34 Coast/Brake Downshift

Number of events	DR
24	7.1

12.1.5.3. Tip out Upshift quick

Table 35 Tip out Upshift quick

Number of events	DR
13	6.9

12.1.5.4. Tip out Upshift slow

Table 36 Tip out Upshift slow

Number of events	DR
13	6.4

12.1.6. Result evaluation

The simulated results are very good and the DR results for gearshifts that can be compared to gearshift from maneuver. Downshift DR is a bit higher than the one from given maneuvers, but this is mainly because here the deceleration is given and followed good, so car behavior may be better than in given maneuvers, where there was not looked detailed into downshift and deceleration behavior there. Main problem with these simulations is with Tip out Upshift slow, because AVL drive is not evaluating the gearshifts as Tip out Upshifts, but as Power on Upshifts. How much does this then affect the DR evaluation cannot be said, but this is a software problem from AVL Drive and is not a problem for this Thesis.

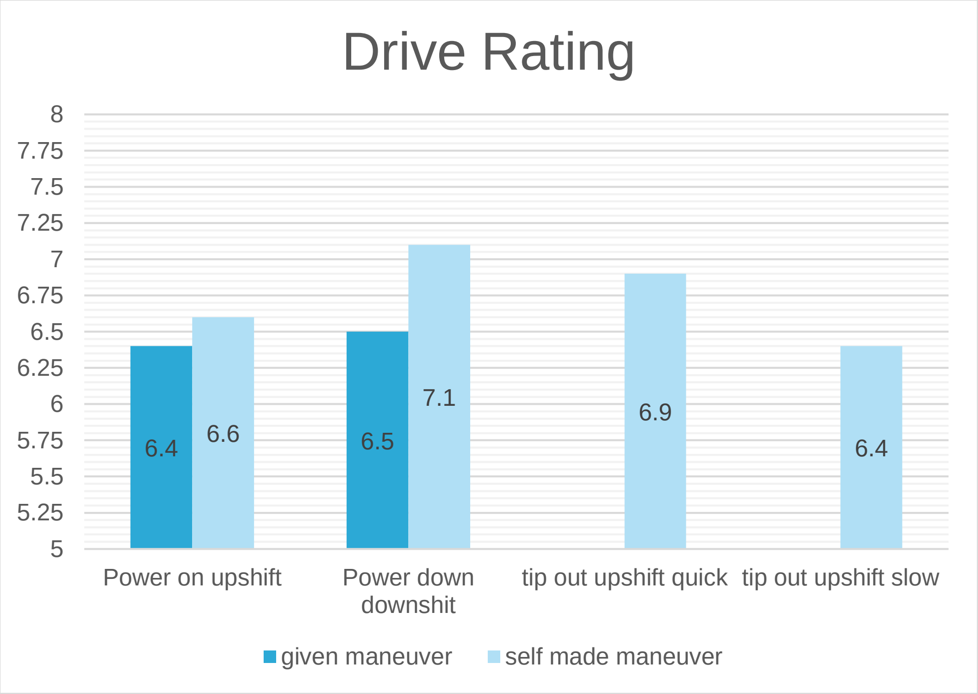


Figure 65 DR comparison between maneuvers

12.2. ECU test testcases

For ECU test the criteria for testcases is the same as in Simulink, just the buildup of the testcase is different.

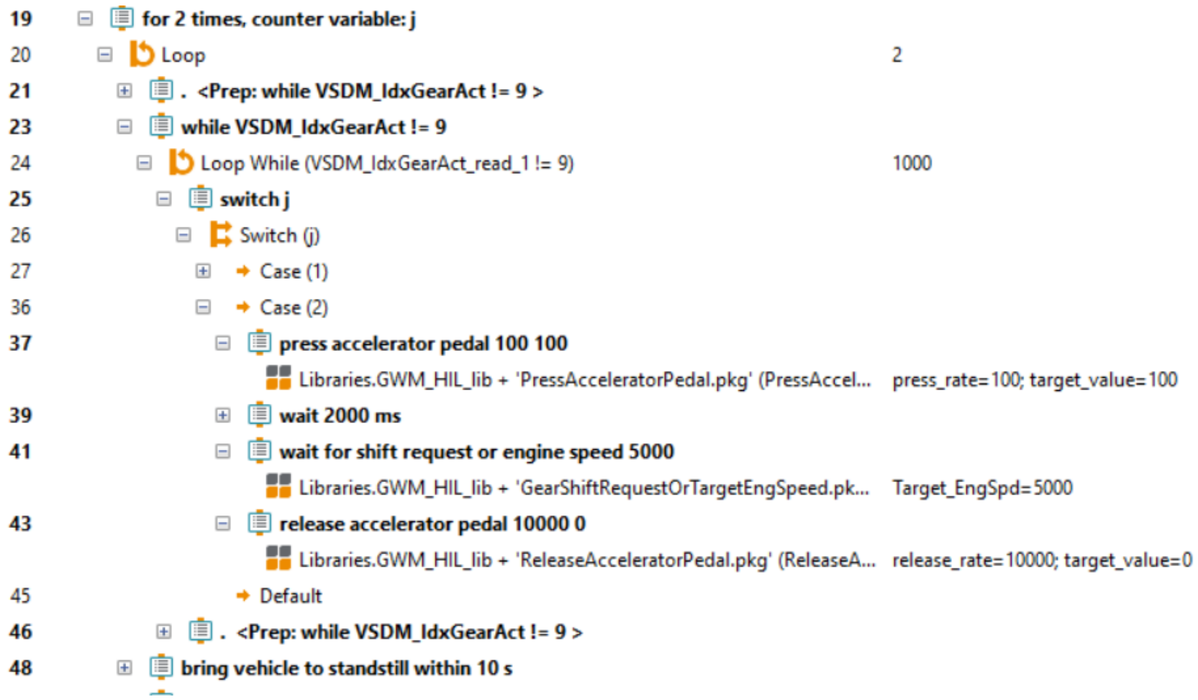
12.2.1. Power on Upshift

```
for 12 times, counter variable: j
  Loop                                                        12          |-> j
    switch j
      Switch (j)
        Case (1)
        Case (2)
        Case (3)
        Case (4)
        Case (5)
        Case (6)
        Case (7)
          press accelerator pedal 100 50
        Case (8)
        Case (9)
        Case (10)
        Case (11)
        Case (12)
        Default
    while acc_above_threshold == True
      Loop While (acc_above_threshold == True)                1000
        check ClCo_StMain == "DrvCtl"  wait until true time out 10000 ms
        . <Prep: if VSDM_IdxGearAct != SSq_IdxGearDesrd >
        . <Prep: if VSDM_IdxGearAct != SSq_IdxGearDesrd >
        if VSDM_IdxGearAct != SSq_IdxGearDesrd
        . <Prep: if VSDM_IdxGearAct == 9 >
        if VSDM_IdxGearAct == 9
        wait 200 ms
        check trailing values extend do test step save and mapping
    bring vehicle to standstill within 10 s
```

Figure 66 ECU test testcase Power on Upshift

6 shows the testcase from chapter 5.3.1 with pedal position 50%. The Vehicle is accelerating with 50% pedal position and doing so until the conditions inside the loop are fulfilled. When all conditions are checked or the acceleration threshold is reached, the model is going out of the loop and braking to standstill. This same loop is happening for all 12 cases of accelerator pedal position.

12.2.2. Tip out Upshift

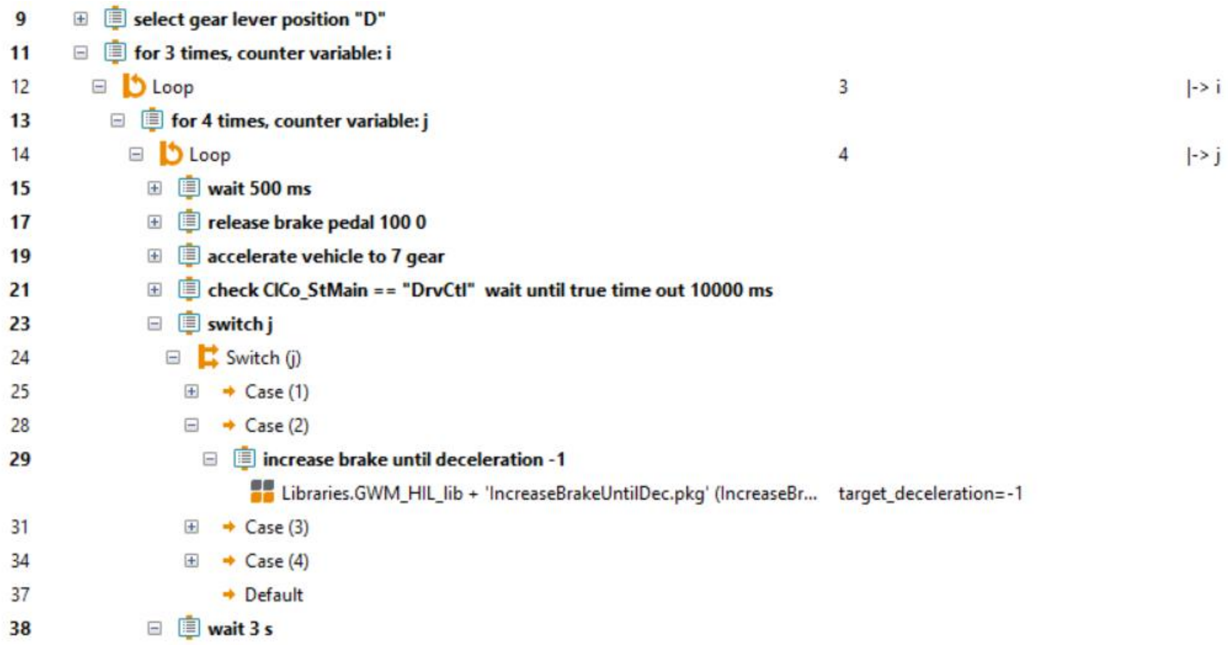


```
19  ⊟ for 2 times, counter variable: j
20    ⊟ Loop                                                                          2
21      ⊞ . <Prep: while VSDM_IdxGearAct != 9 >
23      ⊟ while VSDM_IdxGearAct != 9
24        ⊟ Loop While (VSDM_IdxGearAct_read_1 != 9)                                  1000
25          ⊟ switch j
26            ⊟ Switch (j)
27              ⊞ Case (1)
36              ⊟ Case (2)
37                ⊟ press accelerator pedal 100 100
                      Libraries.GWM_HIL_lib + 'PressAcceleratorPedal.pkg' (PressAccel...    press_rate=100; target_value=100
39                ⊞ wait 2000 ms
41                ⊟ wait for shift request or engine speed 5000
                      Libraries.GWM_HIL_lib + 'GearShiftRequestOrTargetEngSpeed.pk...       Target_EngSpd=5000
43                ⊟ release accelerator pedal 10000 0
                      Libraries.GWM_HIL_lib + 'ReleaseAcceleratorPedal.pkg' (ReleaseA...    release_rate=10000; target_value=0
45                Default
46          ⊞ . <Prep: while VSDM_IdxGearAct != 9 >
48      ⊞ bring vehicle to standstill within 10 s
```

Figure 67 ECU test testcase Tip out Upshift

Similar to Power on Upshift case is also here the main part inside a loop where the conditions of the testcase have to be satisfied. The conditions are the same as in chapter 12.1.2, the only difference here is that the trigger for shift request is not necessary, because of the proper Software, which is triggering the shift request from itself. In ECU test there is no need to make an additional testcase for tip out slow, because the time in which the pedal is disengaged is done with a release rate factor, which can be changed accordingly to the needs of the testcase. The two cases in the loop are one for 50% pedal position and the other one for 100%.

12.2.3. Coast/brake Downshift



```
9   select gear lever position "D"
11  for 3 times, counter variable: i
12    Loop                                                        3       |-> i
13      for 4 times, counter variable: j
14        Loop                                                    4       |-> j
15          wait 500 ms
17          release brake pedal 100 0
19          accelerate vehicle to 7 gear
21          check ClCo_StMain == "DrvCtl"  wait until true time out 10000 ms
23          switch j
24            Switch (j)
25              Case (1)
28              Case (2)
29                increase brake until deceleration -1
                    Libraries.GWM_HIL_lib + 'IncreaseBrakeUntilDec.pkg' (IncreaseBr...   target_deceleration=-1
31              Case (3)
34              Case (4)
37              Default
38          wait 3 s
```

Figure 68 ECU test testcase Coast/Brake Downshift

Same as in previous testcases with ECU test, also this one has all necessary conditions for the testcase in one loop and the conditions are the same as in chapter 12.1.4.. Each case inside the loop is just the different required deceleration.

Unfortunately, DR evaluation with these test cases was not possible because of very limited HiL availability.

13. Conclusion

This thesis shows that drivability evaluation in virtual environment can be done under some limitations and that the results following this evaluation can be sufficiently accurate in relation to real vehicle tests.

Dummy TCU simulations for drivability are good to evaluate the quality of the plant model and identify possible issues with model simulation and identify what can be improved before going to the HiL.

In the considered AT-9 project, the dummy TCU delivered DR evaluation very similar to vehicle tests, so it can be assumed that the dummy TCU is a good approximation when comparing it to an initial SW. It is however difficult to judge in absolute terms the quality of the results, considering that it was simulated and compared with just one vehicle. HiL on the other hand is running with the same software as the vehicle, so if the results here are matching between each other, it can be safe to say, that the plant model is a good representation of real vehicle behavior.

Table 36, Figure 67 and Figure 68 show how much the DR of dummy TCU and HiL has improved during this thesis. The dummy TCU modeling regarding DR is very good and there is not much room for improvement without increasing significantly the complexity of the control algorithm (maybe just getting rid of the torque peak in low gears could allow to improve the DR rating).

The HiL model at the end of the thesis is fine for functional testing and to get an initial feeling on attainable DR values. One major point that still must be improved is the clutch modeling so that the engine speed can follow the given curves, as this represents the biggest deviation between real and modelled behavior. An additional aspect that can be considered subsequently is the impact of acceleration and acceleration disturbances on the DR. Modelling the vehicle in more detail (including suspension system for modelling of vertical acceleration) and including torque disturbances of combustion engine might bring the acceleration level nearer to the results gathered in reals car measurements.

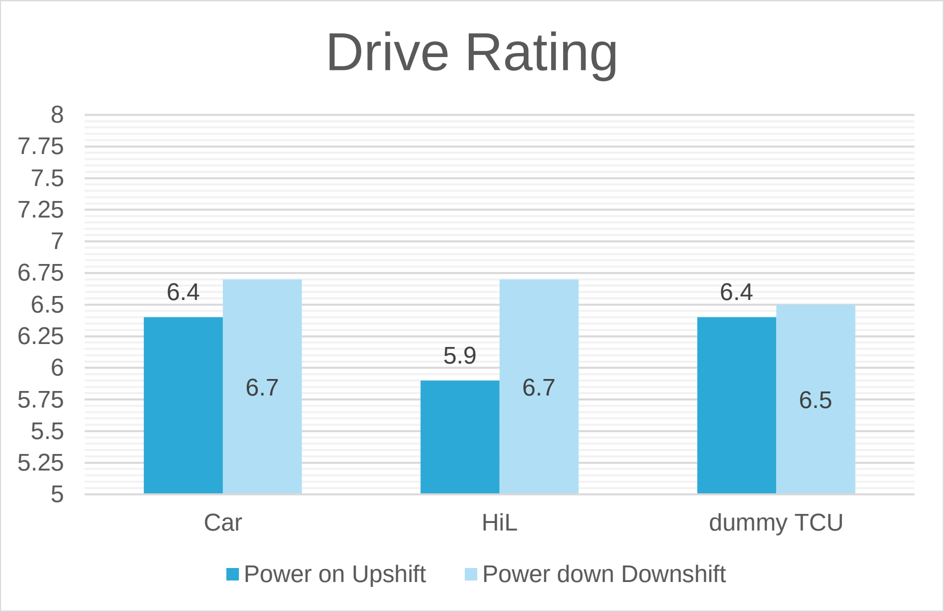


**Figure 69 Overall DR comparison*

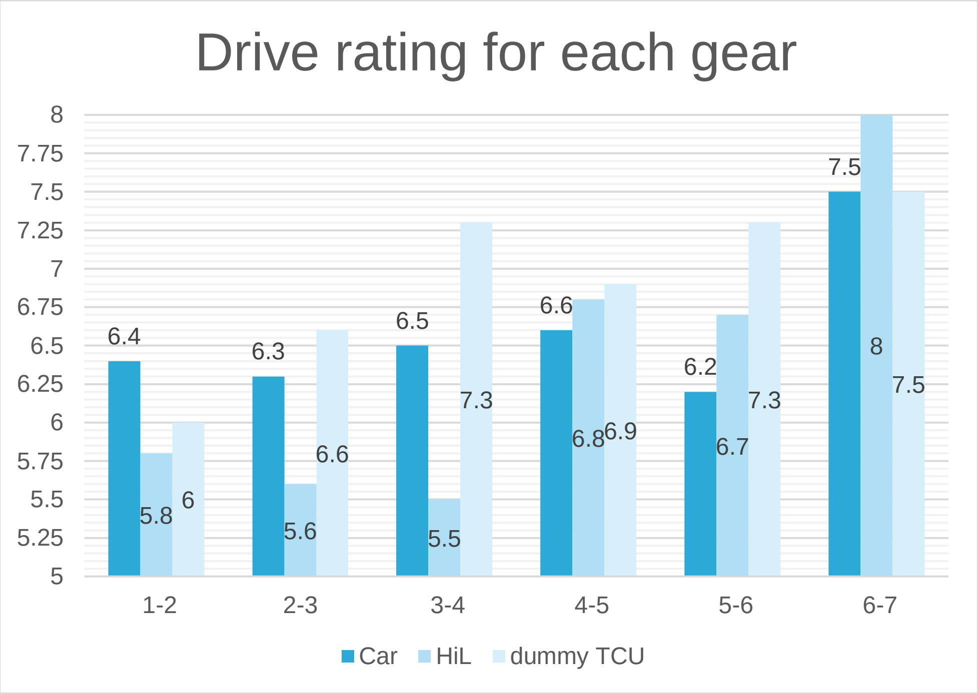


**Figure 70 overall DR for every gear*

**Table 37 Comparing DR from real car evaluation with old and new model for HiL and dummy TCU*

Gearshift	**Events**	**Car DR**	**Old HiL DR**	**New HiL DR**	**Old Dummy TCU DR**	**New Dummy TCU DR**
Power on Upshift	24	6.4	5.6	5.9	5.8	6.4
Power down Downshift	16	6.7	7.0	6.7	7.2	6.5

In conclusion it can be said that the goal of the thesis was reached, AVL DRIVE drivability evaluation in virtual environment can be done. In future developments these simulations can lead to cost reduction, because some simulations can be done much earlier, even before the real car is available and this can reduce development cost and time. Also, test cases driven on simulations are way more exact regarding pedal position, because any failures caused by human nature, e.g. not being always at defined accelerator pedal position or not following the exact deceleration, are excluded here. To get the results even nearer to real vehicle tests, AVL DRIVE evaluation could also be done with AVL VSM [19], which is additional to longitudinal movement, giving the option of lateral acceleration, which is not considered at the moment.

**AVL DR evaluation was done with initial software where no calibration or functional tests were done yet, so lower DR values were expected.*

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15. List of figures

16. List of tables