Combining Powertrain Efficiency and Drivability for Optimizing Hybrid Development

Master’s thesis in Automotive Engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Abstract

It is undisputed that vehicle hybridization has become one of the most prospective solution to the global energy and environmental problems caused by the transport sector. After having experienced a rapid development, Hybrid Electric Vehicles (HEV) are widely recognized by more and more customers and gradually dominating the automobile market by their remarkable performance, fuel economy and emission reduction. To survive the fierce market competition and to meet the increasingly strict emission regulation, many car manufacturers are looking to decrease development time and cost. Part of the actions in order to shorten development time, the demand for virtual optimization and evaluation, as well as early drivability and high level customer experience is needed. This thesis is aimed at exploring the possibility of having access to the drivability evaluation and optimization virtually.

The first part involves identifying all the necessary signals and generating the missing signals. The second part involves establishing the signal connection between GT-Suite and AVL-Drive. The third part involves evaluating the drivability using the AVL-Drive and carrying out the drivability optimization on targeted operation modes.

In total, 12 vehicle signals are requested for a drivability assessment in AVL-Drive and three of them (Brake State, Brake Pedal Position and Accelerator Pedal Position) have been generated successfully. With the help of Matlab, the signal connection between GT-Suite and AVL-Drive has been created and the drivability reference objects of a competitor vehicle and LYNK&CO 01 are provided for comparison. The drivability ratings of engine start and gear shift selected as the targeted operation modes have been improved significantly.

Keywords: Hybrid electric vehicle, Powertrain efficiency, Objective drivability assessment, Vehicle simulation, Optimization

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In the end, I would like to thank my family and my girlfriend for their unfailing support and selfless company which keep me moving forward.

Shengwei Deng, Gothenburg, June 2019

Nomenclature

BCU Braking Control Unit

BMS Battery Management System

DCT Dual Clutch Transmission

DR DRIVE Rating

ECU Engine Control Unit

EM Electric Machine

EMCU Electric Machine Control Unit

EV Electric Vehicle

FHAP Fuzzy Hierarchy Analysis Process

FHEV Full Hybrid Electric Vehicle

HEV Hybrid Electric Vehicle

ICCT International Council of Clean Transportation

ICE Internal Combustion Engine

MBSE Model Based System Engineering

MHEV Mild Hybrid Electric Vehicle

PHEV Plug in Hybrid Electric Vehicle

PID Proportion Integration Differentiation

SOC State of Charge

TCU Transmission Control Unit

WLTC Worldwide harmonized Light vehicles Test Cycle

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1 Introduction

As shown in Figure 1.1, an increasingly strict CO_2 emission regulation is being proposed and enacted worldwide at the time. It can be clearly observed that by 2030 the European Union has distinguished itself by having the lowest CO_2 emission aim of 59 g/km by far, which will pose a huge challenge to all the car manufacturers and force the automotive industry to come up with more solutions.

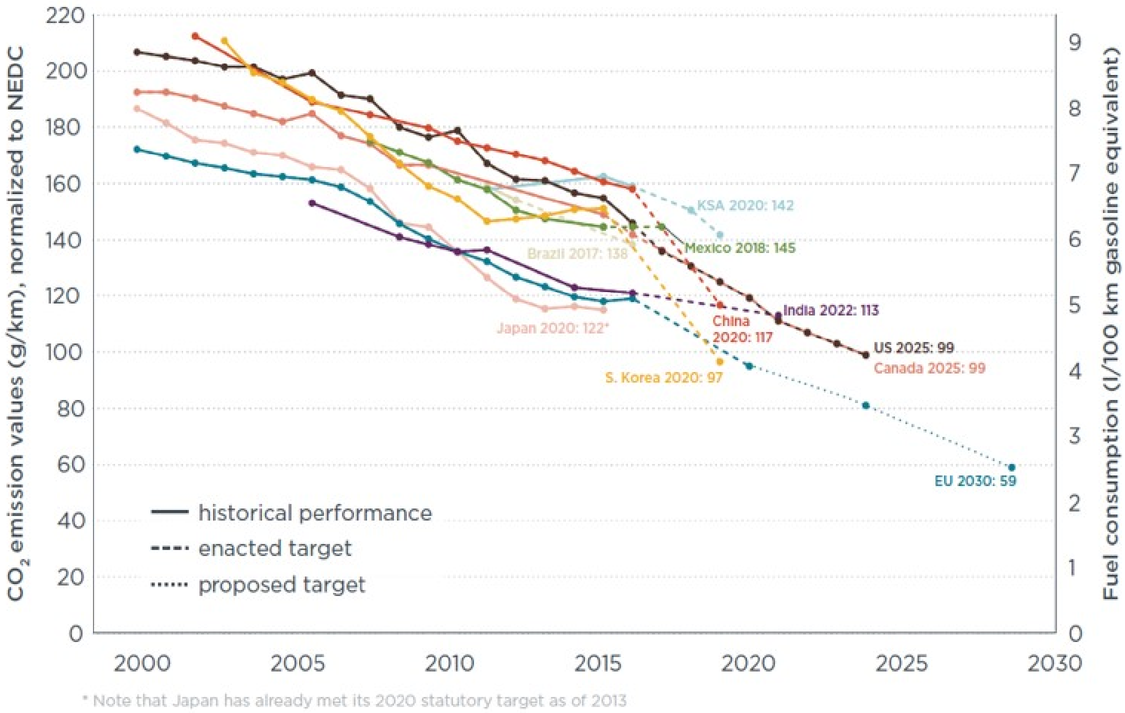

Figure 1.1: Comparison of global CO_2 regulations for new passenger cars[2]

Being a promising development direction in the automotive industry, vehicle hybridization has come into the public's sight and given birth to an extraordinary revolution in the automotive industry. The hybrid electric vehicle combines a high-energy density of internal combustion engine system with an efficient electric propulsion system[3] and is one of the most important products of the vehicle hybridization campaign. So far countless research work has already been conducted on the HEV with a purpose of improving the fuel consumption and emission performance. As shown in Figure 1.2, compared with the conventional vehicle, the fuel consumption of HEV can be dramatically improved by 68% and meanwhile CO_2 emissions can be decreased by 40% maximumly[4]. It is noticeable from Figure 1.2 that largest benefit is found in lower speed driving cycles, such as Baqubah and FTP while in high speed driving the benefit, such as for US06HWY, is smaller.

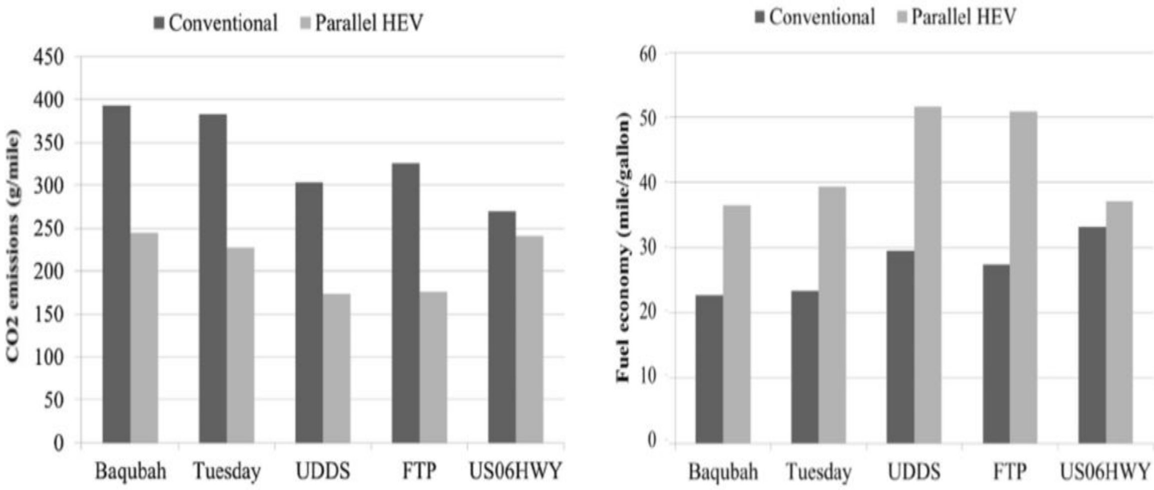

Figure 1.2: Performance comparison between hybrid vehicle and conventional vehicle in different driving cycles[4]

1.1 Background

Figure 1.3 shows that new energy vehicles (MHEV, FHEV, PHEV and EV) are occupying a growing part of the total automotive market share over time and HEV is possessing a high potential among all the new vehicle consepts in the current market.

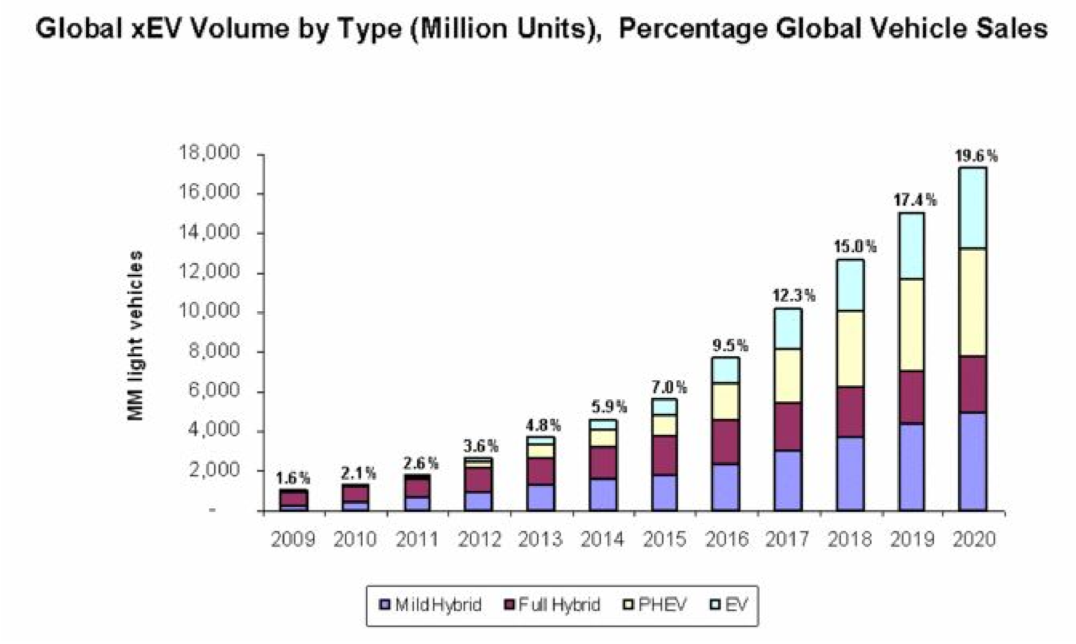

Figure 1.3: Global new energy vehicle market projections[5]

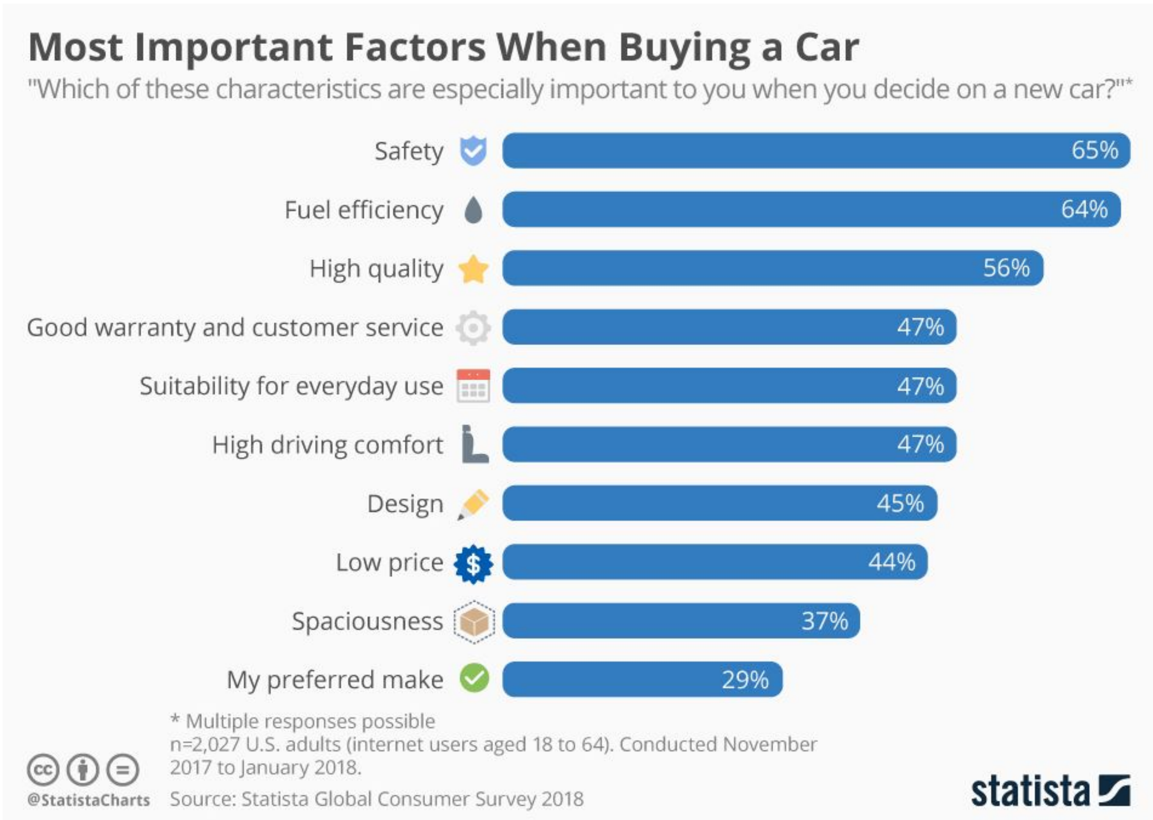

Figure 1.4: Vehicle purchasing criteria[6]

As is shown in Figure 1.4, drivability has also become a critical factor taken into account by customers when purchasing a new car in the US. Compared with conventional vehicles, hybrid vehicles have much more frequent engine onoff and other transient switch which are highly related with the drivability. In order to further step up the competitiveness of hybrid vehicles, it is of great significance to carry out work to meet the customer demands on high drivability. At the early period, the drivability assessment was mostly conducted in a subjective way where the experienced driver gave the ratings with a range from 0 to 10 based on the personal perception in real testing cases[7]. Obviously, the results of subjective assessment possess a high level randomness and is prone to influence by a wide range of uncontrollable factors. Driven by the growing request for developing a more reliable and general drivability evaluation system, the objective assessment has gradually prevailed and is nowadays widely accepted by the car manufacturers. Anstalt für Verbrennungskraftmaschinen List, short AVL, a private owned engineering company, has been taken to the forefront of objective drivability assessment by AVL-Drive which is one of the most powerful objective drivability evaluation tools and also capable of cooperating with vehicle simulation tools to complete the drivability assessment in an entirely virtual environment[8]. With the capability of drivability assessment extended from road testing to the lab, the achievements on drivability analysis and optimization has emerged in large numbers and are mainly located in the controller and strategy development. To improve the drivability during the vehicle start-up, a multiple-model predictive controller has been developed to predict the reference engine torque and clutch friction torque[9]. Nevertheless, due to the complexity of the hybrid powertrain configuration and increasingly advanced control strategies, the assessment and optimization of drivability are continuously raising new questions to the automotive industry.

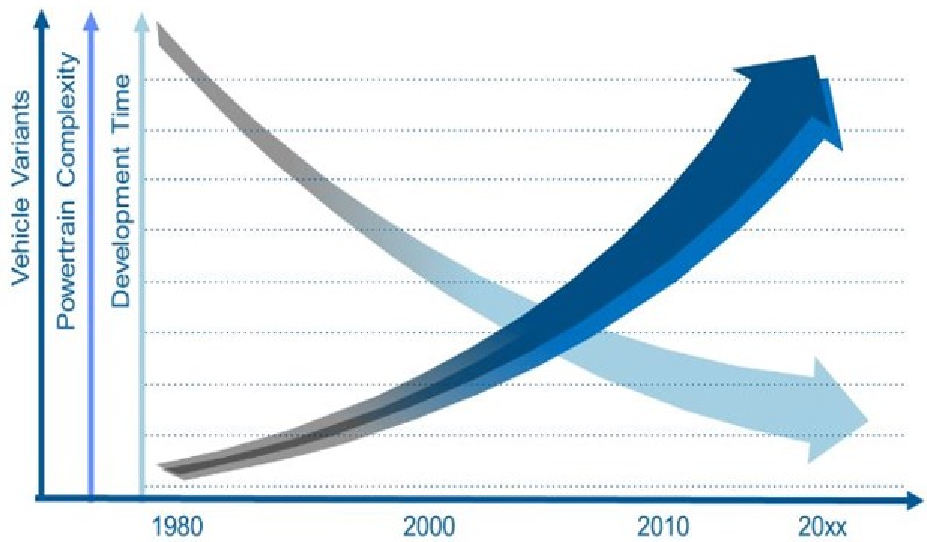

Figure 1.5: Requirements of automotive market[11]

As shown in Figure 1.5, a shorter vehicle development process is requested by automotive market in order to meet the market demands. The automotive players are paying enormous efforts on shrinking the development process to be able to launch their products in time. With a frontloading strategy, the vehicle development process can be shortened significantly by moving the development work of drivability and other vehicle attributes to the early concept development stage.

1.2 Aim

The aim of this thesis is to explore the possibility of having access to virtual drivability assessment at the early concept development stage and optimize the vehicle model towards drivability.

1.3 Procedures

The whole thesis project can be split into four substeps shown below:

- Collect all the necessary signals for a drivability assessment and develop the missing signals
- Establish the signal connection between GT-Suite and AVL-Drive
- Construct reference objects based on the real measurement signals
- Evaluate and optimize the drivability of targeted operation modes

1.4 Focus and Limitations

The focus of the thesis is to provide a general instruction on virtual objective drivability assessment and reference for taking drivability into account at the early model development. Due to the limited time, it is not practical to look into and optimize the drivability in all operation modes. The accuracy and correctness of the optimization can be limited by the complexity of the vehicle model.

1.5 Involved Tools

- **GT-Suite**: Developed by Gamma Technologies, GT-Suite is a leading vehicle modelling and simulation tool widely used in the automotive industry. In this project, it is used to simulate the pre-defined driving cases and generate corresponding vehicle signals.
- **Matlab**: Matlab developed by MathWorks is an advanced numerical computation tool and has been considered as one of the world's most popular programming languages. In this project, it serves as a data processor.
- **AVL-Drive**: Anstalt für Verbrennungskraftmaschinen List, founded in 1948, is a world-leading automotive consulting company and an independent research institute. It is recognized as the largest privately owned company for

the powertrain development, testing system technology and instrumentation. Being one of the most famous software product of AVL and a dedicated tool for drivability assessment, AVL-Drive is developed with a focus on objective real-time evaluation and quality control based on the experience coming from the vehicle benchmarks and drivability development projects[1]. In this project, it is applied to objective drivability evaluation and optimization.

2

Theory

In this chapter, the involved theoretical basis and related background will be briefly introduced. The contents consist of two parts (Hybrid Powertrain and Drivability). In the hybrid powertrain part, different hybrid configuration, dual clutch transmission and driving cycles will be presented. In the drivability part, two frequently-used assessment methods of drivability (Subjective Assessment and Objective Assessment) will be clarified in detail.

2.1 Hybrid Configuration

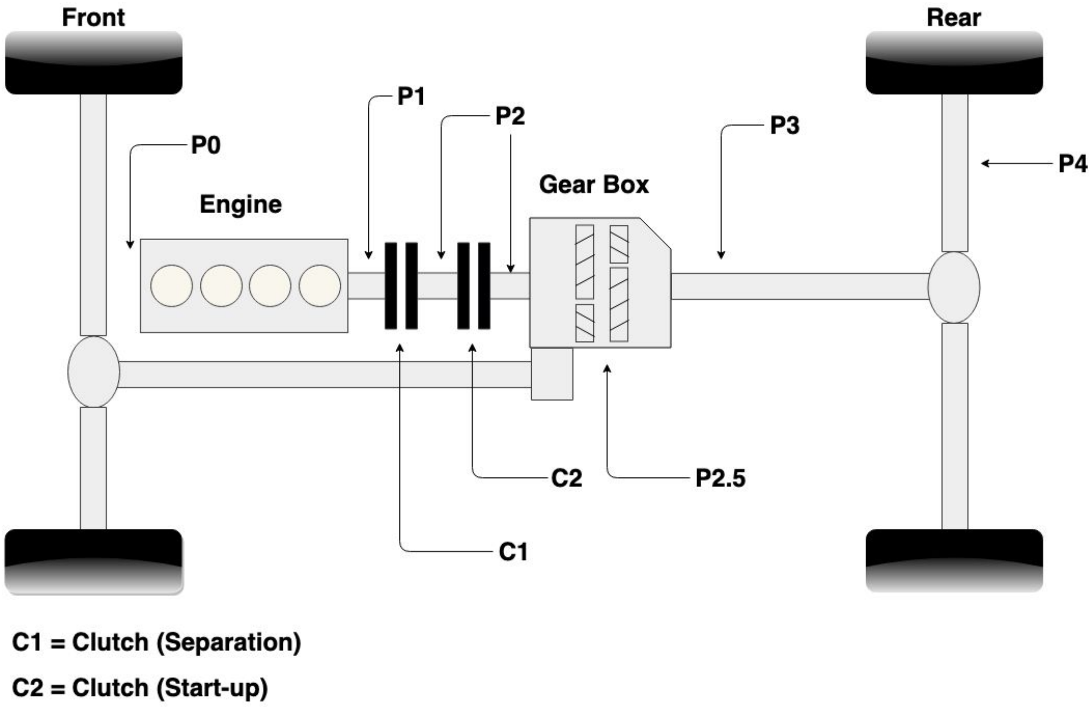

Figure 2.1: Hybrid configuration overview

Hybrid vehicle concepts can be classified according to the position of the electric machine and coupling points as shown in Figure 2.1:

- **P0**: The electric machine is mechanically coupled with engine through a belt and integrated into the existing engine accessories system. The component integration cost can be reduced by minimum impact on the layout of the conventional vehicle. However, due to the incapability of disconnecting the electric machine from the engine, the pure electric driving mode is not available and the max power performance will also be limited by the belt slip.

- **P1**: The electric machine is directly mounted on the engine crankshaft. Because of the rigid connection between the electric machine and the engine, the electric machine can also function as a starter and assist the driving with high efficiency. The biggest disadvantage of this solution is that the max power performance will be limited by the torque capacity of the electric machine.
- **P2**: The electric machine is an in-line machine sitting on the input shaft of the transmission. The vehicle can be driven by the electric machine exclusively and the energy recuperation potential will be increased as well since the electric machine is placed after the clutch. Since the electric machine is placed before the transmission input, the electric machine can have access to all gear numbers and can be downsized with a smaller torque capacity.
- **P2.5**: The electric machine is an off-axis machine connected to the input shaft of the even gear side of the dual clutch transmission via some types of gear, chain and belt. This configuration can effectively mitigate the unsteadiness during the switch of power source and step up the integration level. In this solution, the electric machine can only select the even gear numbers.
- **P3**: The electric machine is located between the transmission and differential shaft and directly coupled with the output shaft of the transmission. The efficiency of electric drive and energy recuperation is improved by skipping the transmission losses. Due to the direct mechanical connection with axle, the electric machine can not function as a engine starter.
- **P4**: From a structural point of view, this configuration is quite similar to P3 with an electric machine located after transmission. Concretely, the electric machine is mechanically linked with the rear axle, which makes four-wheel drive possible and also has a positive effect on steering capability. Since the engine and electric machine are attached to different axles, the switch between pure electric mode and conventional driving mode can not be actuated flexibly.

2.2 Dual Clutch Transmission

The dual clutch transmission is one of the most remarkable developments in the transmission technology[12]. By providing good shift quality and high transmission efficiency, the DCT has been widely implemented in the hybrid powertrain configuration and considered as a brilliant developing direction in the research area of transmission[13]. The engine can be engaged in powering the vehicle through either odd clutch or even clutch. In the GEELY Dual Clutch Transmission-Hybrid configuration, the electric machine only has the access to the even gear number since it is mechanically coupled with the even input shaft as shown in Figure 2.2. Through the engagement and disengagement of two clutches different gear combinations can be achieved, which significantly extends the range of gear ratio. During the gear shift, the targeted gear will be selected in advance by the corresponding synchronizer. With the help of gear pre-selection the rotation speed of the transmission input shaft can reach the expected level much early and the engine speed and the clutch torque can be controlled properly to decrease the friction losses and shrink the engagement duration which give a smooth and efficient gear shift process.

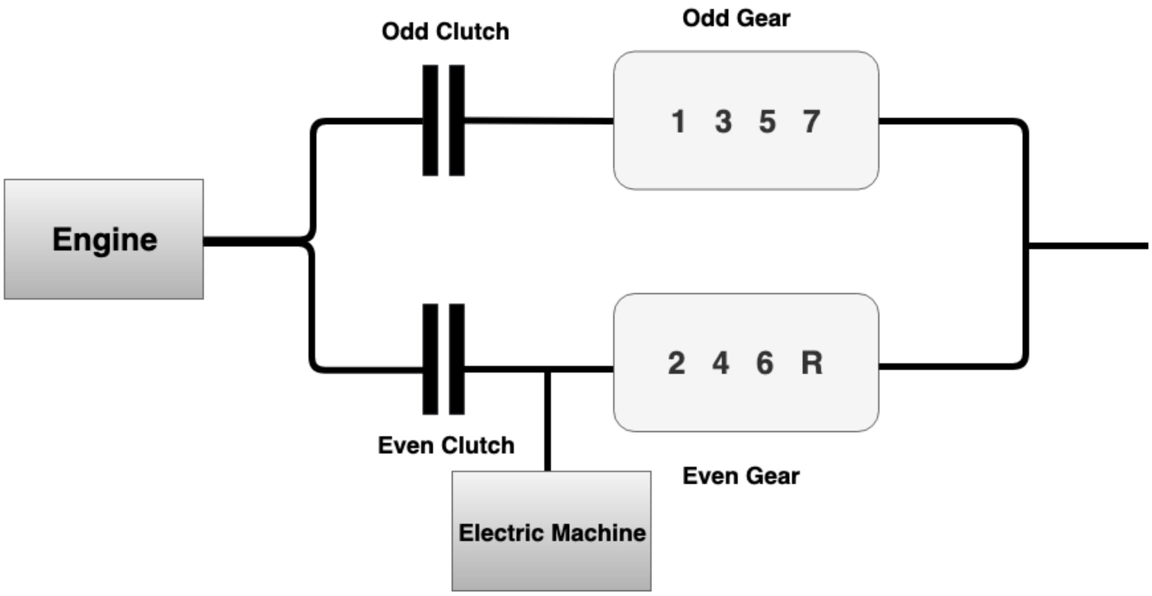

Figure 2.2: Schematic representation of GEELY 7DCT-Hybrid transmission

2.3 Drivability

The drivability indicates a subjective and comprehensive perception of the driver during the interactive operation between the driver and vehicle, mostly associated with vehicle acceleration[14]. A good drivability can have a positive effect on the driving pleasure and significantly enhances the buying inclination of the customers[15]. The theoretical principles behind drivability can be uncovered by the closed-loop control system shown in Figure 2.3. During the driving process, the driver is mainly responsible for perceiving the information coming from outside and operates the vehicle properly based on personal judgment. The driver output such as accelerator pedal position will be sent to the vehicle control unit to update the vehicle behaviour for a consistency with the driver intention. The drivability describes how satisfied the driver could be with this transition process.

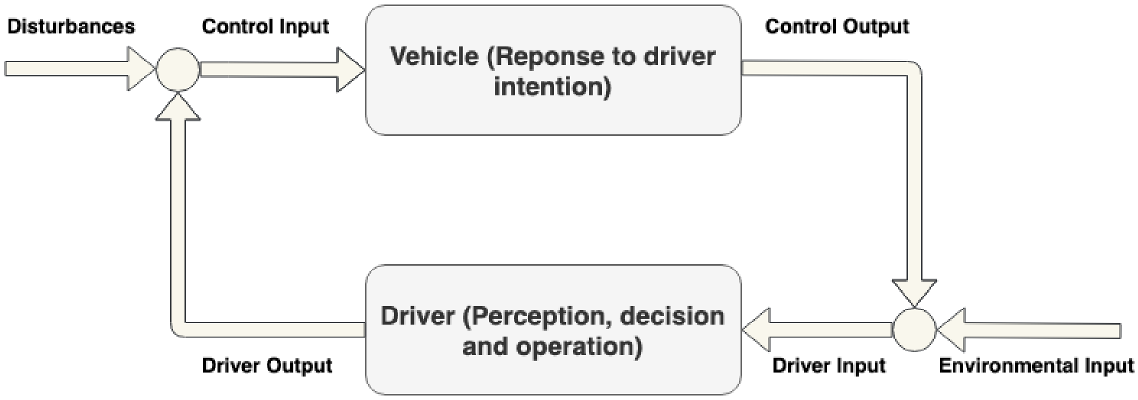

Figure 2.3: Driver-Vehicle-Environment closed-loop system

2.4 Subjective Drivability Assessment

Currently, the subjective drivability assessment is still widely favoured by many car manufacturers. Since the drivability is essentially involved with the subjective feeling of the driver, the drivability assessment can also be carried out in a subjective way. At the beginning, the assessment will be divided into the individual evaluation of several operation modes the driver is able to recognize as is shown in Figure 2.4 and a subjective rating with a range from 0 to 10 will be given to each operation mode respectively by expert drivers based on their previous experience.

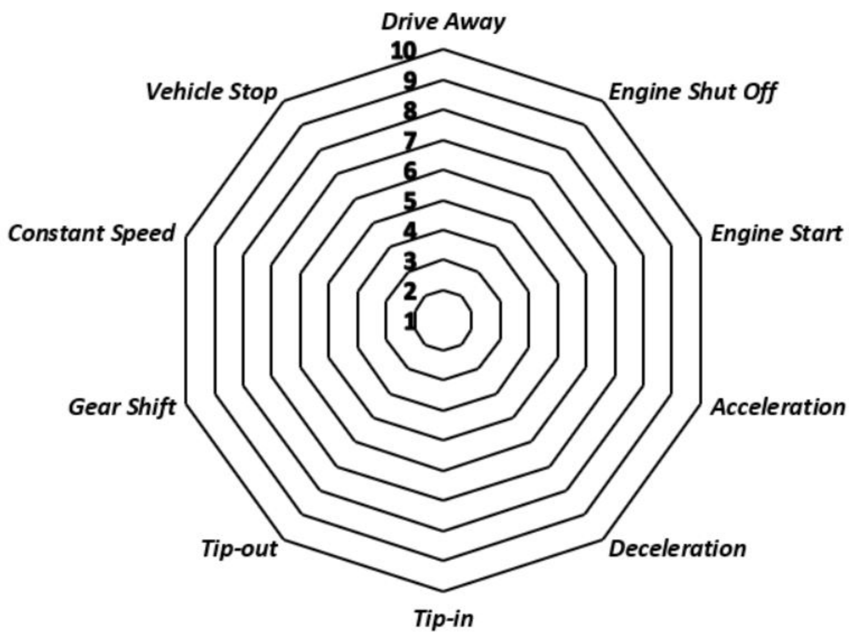

Figure 2.4: Operation modes of subjective assessment

To acquire the final drivability result, all the sub ratings will be processed according to a pre-defined assessment system. Nevertheless, how to reasonably establish the evaluation system for subjective assessment has already eluded the automotive industry for many years and with the rapid advance in numerical analysis and computation, lots of promising solutions have been proposed by scientists and researchers: an advanced subjective evaluation system based on the neural network has been presented by Schoeggl[15] and Liu made full use of fuzzy hierarchy analysis process (FAHP) to construct a weight-based subjective evaluation system[16]. However, the subjective assessment will be limited by the variation of the environmental factors and the individual difference of the evaluators and does not possess enough universality.

2.5 Objective Drivability Assessment

With the request for an united and comparable drivability evaluation system, the objective method has gained increasingly attention and already been developed in the past many years[17]. Similarly, the drivability assessment will be split into several individual operation modes and each operation mode has corresponding evaluation criteria which can appropriately present the driver perception and reflect the degree of the satisfaction as well[18][19]. Based on the signals collected from real vehicle testing or simulation output to describe the vehicle behavior and capture the criteria, the rating process will be conducted in some specialized evaluation tools such as AVL-Drive instead of directly being rated by the human perception.

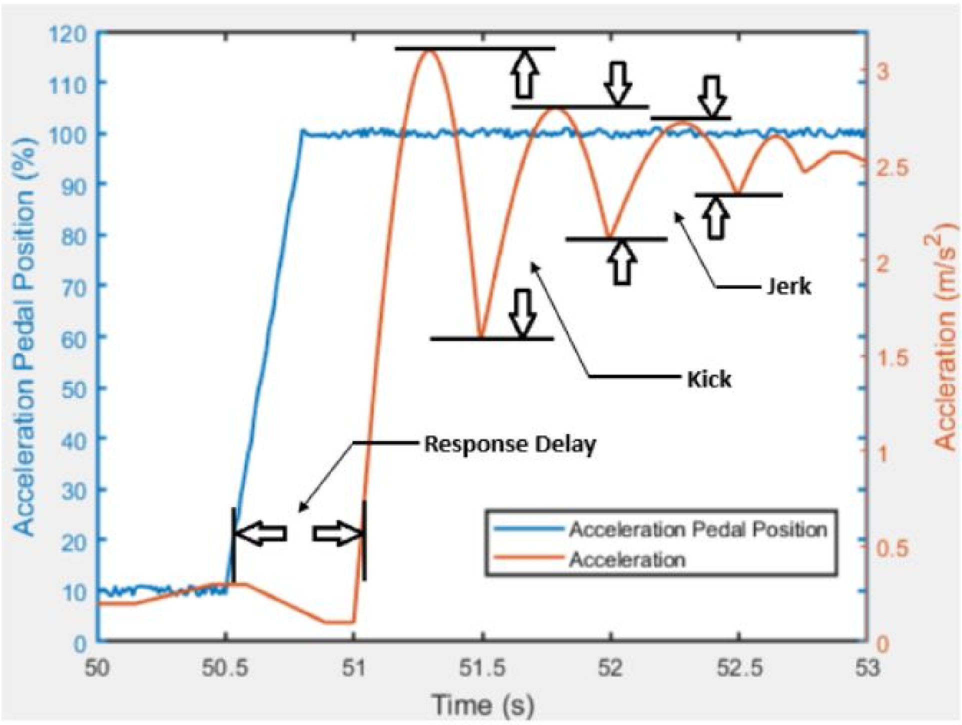

Figure 2.5: Acceleration behavior with a full accelerator pedal input

Figure 2.5 shows a typical principle of drivability evaluation in the operation mode with a sharp pedal increase. Based on the acceleration and pedal position input, three critical criteria (Response Delay, Kick and Jerk) highly related with the driver feeling are evaluated and weighted to delivery a final drivability rating:

- **Response Delay**: The response delay measures the time duration between the accelerator pedal actuation and first obvious acceleration increase and a longer response delay will lead to a lower drivability rating.
- **Kick**: The kick means the first remarkable acceleration decrease and a larger acceleration drop will generate a lower drivability rating.
- **Jerk**: The jerk is defined as a transition process from the oscillating acceleration phase to the stable acceleration phase. A larger fluctuation amplitude as well as a longer duration of the jerk will lower the drivability rating.

3
Methodology

3.1 GT-Suite

Developed by the Gamma Technologies, GT-Suite has become a leading and well-known Model Based System Engineering (MBSE) tool which is recognized worldwide as the industry standard for system simulation. By providing a comprehensive fundamental set of component libraries, the GT-Suite is able to simulate a wide range of general systems covering thermal , mechanical, electrical, chemistry and control areas. In the automotive industry, the GT-Suite distinguishes itself as a professional vehicle modelling and simulation tool with a object-oriented user interface. With the GT-Suite, vehicle architecture can be simply established by connecting individual component template selected from the object library and feeding the necessary parameters into the corresponding template to evaluate and analyze the fuel consumption, emission performance and other critical vehicle attributes. On top of that, the GT-Suite makes it accessible to integrate subsystems such as cooling system and thermal management system into the whole vehicle model for an advanced attribute analysis and strategy optimization.

3.2 AVL-Drive

The AVL-Drive is a professional tool for objective drivability assessment and developed by AVL List GmbH in order to enhance the flexibility of drivability development during the whole vehicle development process. The AVL-Drive system is applicable to various vehicle types (Passenger Car, Bus, Truck, Motorcycle and Tractor) and a wide range of transmission systems including automatic transmission, double clutch transmission, manual transmission and dedicated hybrid transmission. Based on the calculated parameter values, the drivability is evaluated at criteria level and described by means of DRIVE Rating (DR) from 1 to 10 as shown in Figure 3.1.

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 3.1: Drivability rating system of AVL-Drive

Figure 3.2 shows a clear picture of how AVL-Drive evaluates the drivability in an objective way. The gear shift is taken as an example. At the bottom level, some critical criteria such as shift delay, traction reduction and shift duration will be calculated based on the vehicle signal input. After that, the related criteria with the corresponding weighting factor will be combined and analyzed to give a drivability rating of sub operation modes. In the same way, the drivability rating of main operation modes will be determined by weighting the rating of each sub operation mode. The total drivability rating is a weighted rating of main operation modes.

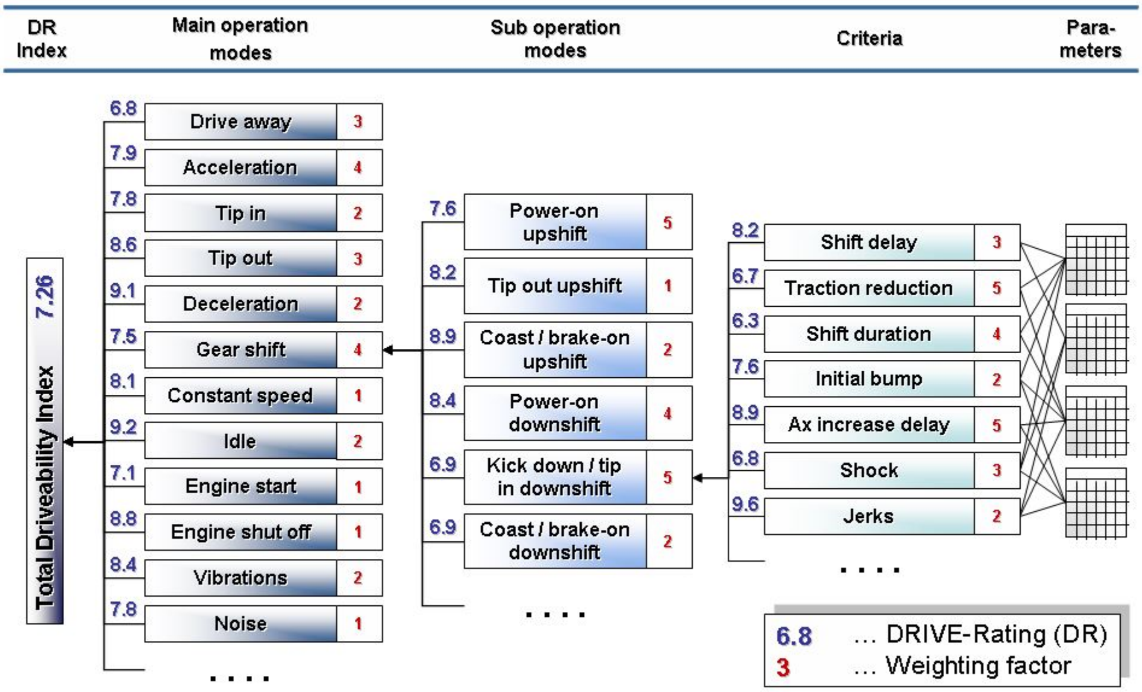

Figure 3.2: Drivability evaluation principle of AVL-Drive

3.3 Tool Connection

As mentioned previously, GT-Suite, Matlab and AVL-Drive are the main involved software tools in this thesis project and a certain series of vehicle signals need to be sent into AVL-Drive in order to objectively evaluate the drivability. However, the AVL-Drive is incapable of accepting the signal data directly from GT-Suite. To estabilish the data connection between the GT-Suite and AVL-Drive, it is figured out that the signal data coming from the GT-Suite need to be saved in the Matlab and then transported to the AVL-Drive. The mutual cooperation between the above tools is illustrated in Figure 3.3.

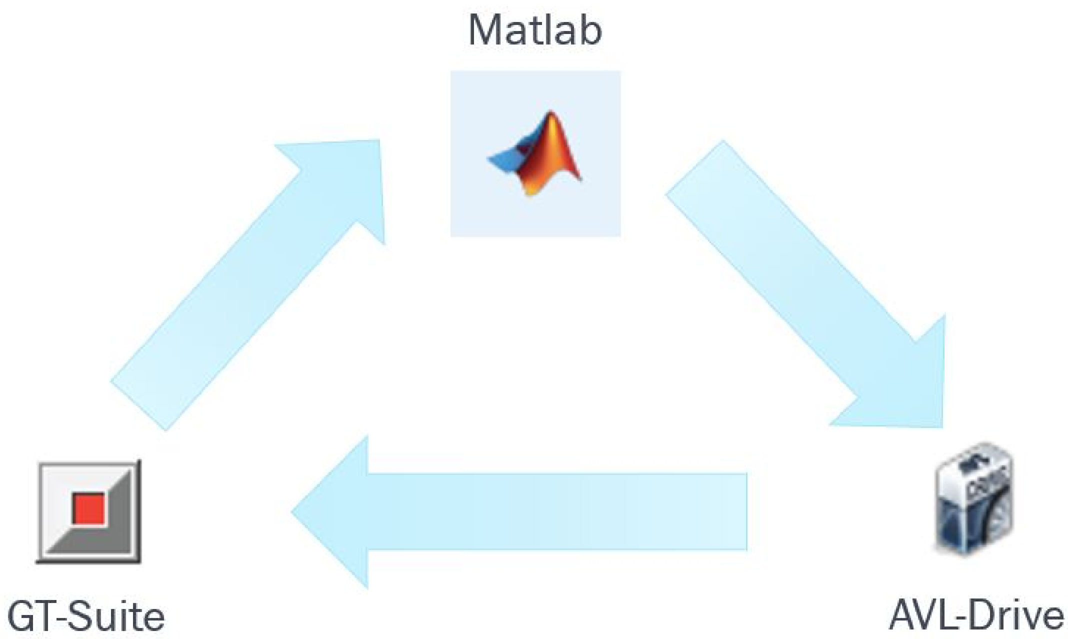

Figure 3.3: Schematic diagram of tool connection

- **GT-Suite** $\longrightarrow$ **Matlab**: The vehicle signals are generated by running the corresponding simulation in the GT-Suite and exported from GT-Post. After that the vehicle signals will be sent into Matlab and saved as a data file.
- **Matlab** $\longrightarrow$ **AVL-Drive**: The data file will be transported to the AVL-Drive and AVL-Drive will conduct the objective drivability assessment based on these data input.
- **AVL-Drive** $\longrightarrow$ **GT-Suite**: The divability assessment results given by the AVL-Drive will be analyzed comprehensively and a drivability feedback will be sent to the GT-Suite to instruct the model optimization.

3.4 Vehicle Model

The investigated vehicle is LYNK&CO 01 HEV with a 1.5 litre engine and seven speed dual clutch transmission system. The complete vehicle is modelled in the GT-Suite environment in order to generate the necessary vehicle signals for the later drivability assessment and the model layout with a P2.5 hybrid architecture is shown in Figure 3.4. The engine is connected to a 12V starter motor and transmission system and controlled by the engine control unit (ECU). The electric traction system including electric machine, battery, Electric Machine Control Unit (EMCU) and Battery Management System (BMS) is integrated into the transmission system which is mechanically linked with vehicle body. The driver block is actually a PID controller which calculates the power or torque request based on the pre-defined target speed and controls the vehicle by sending out actuator signals. The hybrid control strategy instructs the vehicle to run at the optimal driving mode at current condition and is encapsulated in the state selection block.

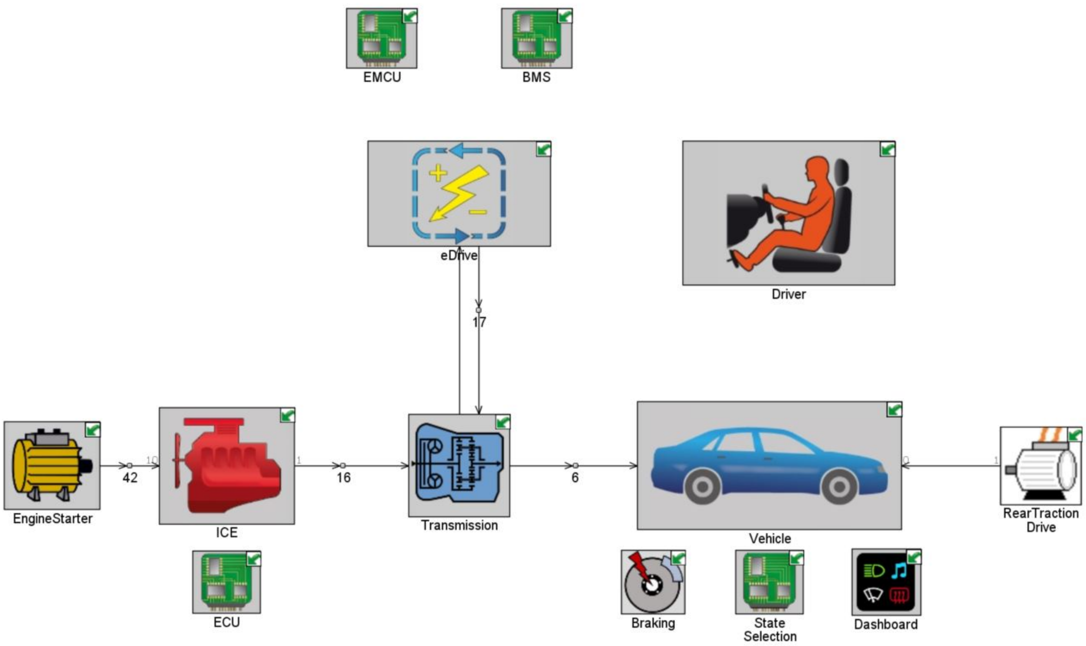

Figure 3.4: Vehicle model in the GT-Suite

To enable a better understanding of the vehicle model, the key model blocks are introduced in details and corresponding parameters are listed as well:

3.4.1 Engine

A map-based engine model is constructed in the GT-Suite and the model layout is shown in Figure 3.5. The mechanical output map, engine friction map and fuel consumption map are requested by the engine template in order to look up the engine torque, engine friction force and fuel performance respectively at a specific operating point. As shown in the figure below, the engine is driven by an engine starter (Part 42) and transmits the torque to the transmission system (Part 16). The engine pedal position signal determined by ECU will be fed to engine template to instruct the engine to work at an expected operating point and meanwhile some engine signals such as engine speed, engine state and engine maximum torque at current speed will be sent out.

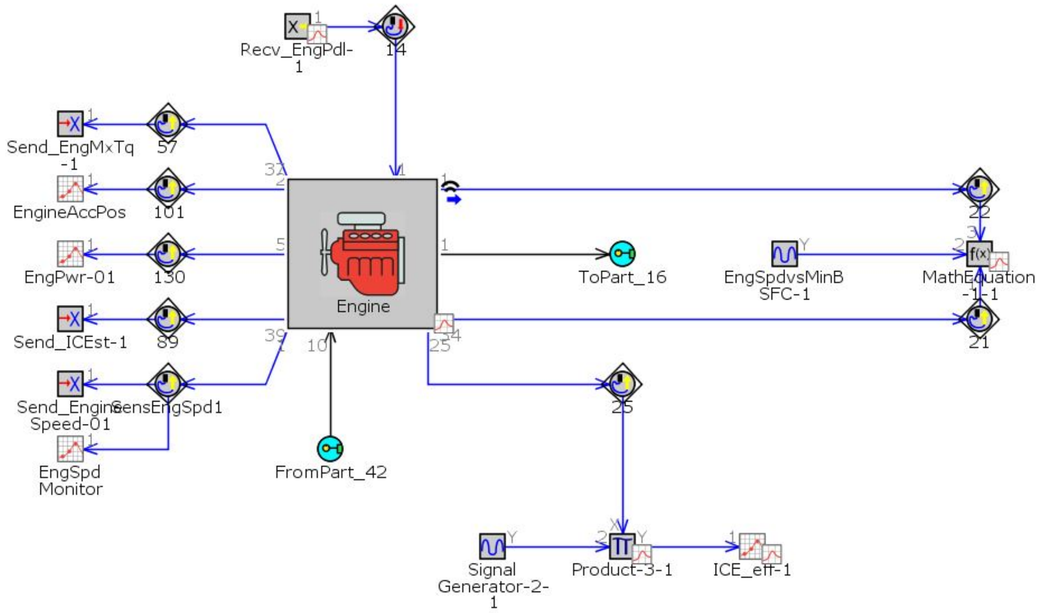

Figure 3.5: Engine model in the GT-Suite

To specify the engine, beside the engine maps some important engine parameters are required as well and listed in Table 3.1:

Table 3.1: Requested engine parameters

Engine Parameters	*Parameter Value*
Engine Stroke (-)	4
Engine Displacement (L)	1.5
Engine Inertia (kg·m^2)	0.15
Initial Engine Speed (RPM)	0

3.4.2 Transmission System

The model of seven speed dual clutch transmission system is created and its profile is shown in Figure 3.6. The transmission system is mechanically connected with engine (Part 16), electric machine (Part 17) mounted on the even gear side and vehicle body (Part 6) in order to transmit the torque from power sources to the wheels. As shown in the figure, a group of related component templates are used and linked with each other:

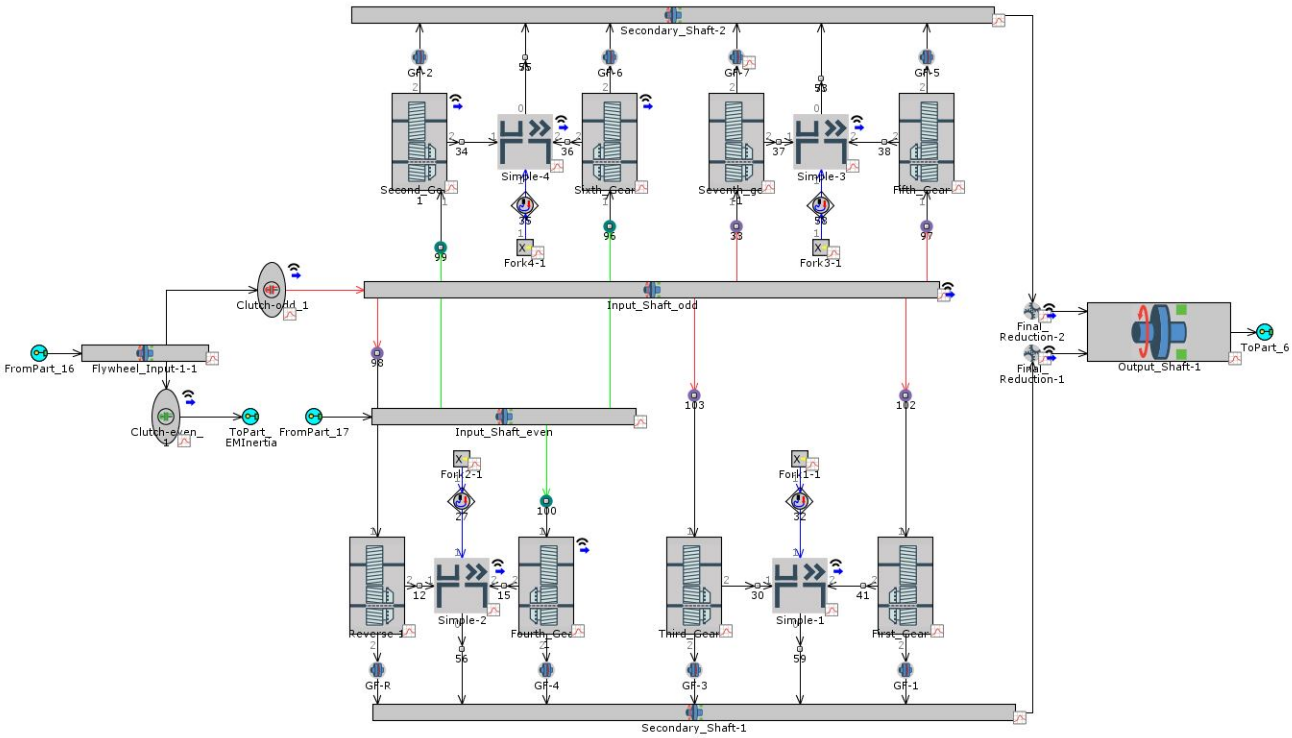

Figure 3.6: Transmission system model in the GT-Suite

- **Gear Pair**: The gear pair is responsible for torque and rotating speed transmission by a certain gear ratio and gear efficiency. This can be described by the mathematical equations shown below:

$$T_{output} = T_{input} \cdot r \cdot \eta \tag{3.1}$$

$$w_{output} = \frac{w_{input}}{r} \tag{3.2}$$

Where the T_{output} is the output torque of gear pair, T_{input} is the input torque of gear pair, w_{output} is the output speed of gear pair, w_{input} is the input speed of gear pair, r is the gear ratio and η is the gear efficiency.

- **Clutch**: In the dual clutch transmission system, the gear numbers are divided into two groups (odd gears and even gears). The odd clutch is subjective to the odd gears and the even clutch is subjective to the even gears, and they are both in charge of engagement and disengagement of the engine. The clutch is controlled by the transmission control unit (TCU) and modelled based on the torque capacity which specifies the maximum torque the clutch can transmit during the clutch engagement and disengagement process.
- **Synchronizer**: The synchronizer is placed between each two gear pairs and is responsible for the gear pre-selection. At the very beginning of the gear shift, the synchronizer will get the synchronizer command signal from the TCU and starts sliding into the target gear number to enable a smoother gear shift process. Currently, the synchronnizer is simply modelled by specifying the synchronization duration.
- **Shaft**: The shafts are used for mechanical connections between different moving part and present the rotation characteristics of the transmission system.

3.4.3 Vehicle

As shown in Figure 3.7, the vehicle is linked with dual clutch transmission system (Part 6) through the driving shaft and rear driving system as well in order to get the traction torque. The vehicle model uncovers the torque transportation path from the transmission system to the vehicle wheels through a series of mechanical connections. The involved component templates in the vehicle model are listed and introduced below:

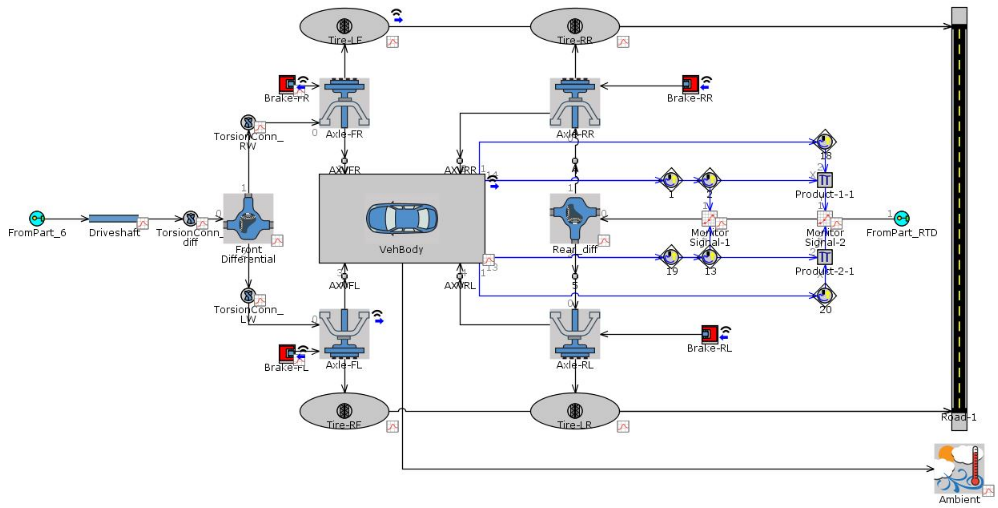

Figure 3.7: Vehicle template in the GT-Suite

- **Vehicle Body**: The vehicle body template indicates the basic vehicle parameters as well as vehicle geometric characteristics. The vehicle specification such as curb mass, vehicle dimensions, frontal area and axle geometry are the main input of this template.

- **Axle**: The axle template is responsible for connecting vehicle body with tires and requests the moment of inertia as the data input.
- **Tire**: The tire template specifies the interaction characteristics between the vehicle and road with the parameter input of rolling resistance, tire traction and rolling effective radius.
- **Brake**: The brake template receives the braking command signal from braking control unit (BCU) and functions as a braking actuator to decrease the vehicle speed. In order to delivery the desired braking torque, the friction characteristics needs to be defined in the template.
- **Road**: In the road template, the road attributes and characteristics such as road gradient are defined.

3.4.4 Electric Traction System

Being one part of the propulsion system in the hybrid electric vehicle, the electric traction system including battery, electric machine and their corresponding control unit is responsible for providing the electrical power to drive the vehicle and storing the electrical energy.

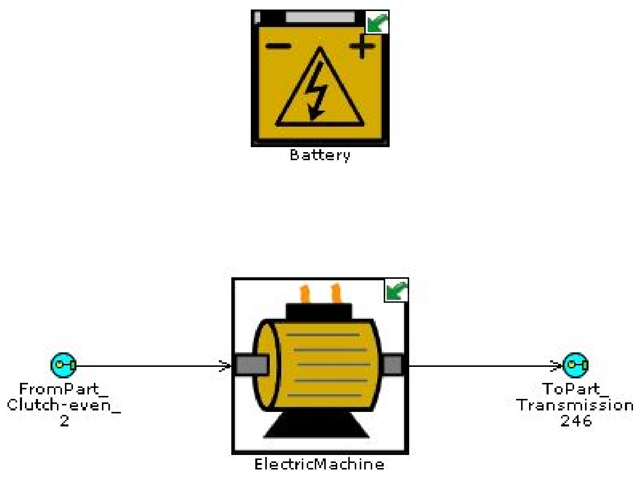

Figure 3.8: Electric traction model in the GT-Suite

As shown in Figure 3.8, the electric machine is placed between the even clutch and even gear pairs and is connected with the battery electrically.

- **Electric Machine**: The electric machine can work as either a traction motor to power the vehicle or a generator to charge the battery according to the hybrid control strategy. Concretely, the electric machine is modelled by a brake torque-based control mode which means the signal of brake torque request determined by the electric machine control unit will be sent to the electric machine and enable the electric machine to deliver the expected torque. In addition, the efficiency map and torque boundary curve are also requested by electric machine template.
- **Battery**: The battery is responsible for storing the electrical energy and outputting the electrical power by discharging if needed. In this vehicle model, the battery is modelled based on a power demand-based control mode which means the signal of battery power demand coming from the battery control unit will be sent to the battery template and instruct the battery to be charged or discharged in order to achieve a targeted state of charge. In the battery template, the battery capacity, circuit parameters and battery efficiency need to be specified.

The parameters settings of electric machine and battery are shown in Table 3.2 below:

Table 3.2: Requested electric traction system parameters

Electric Traction System Parameters	*Parameter Value*
Maximum Electric Machine Torque (N·m)	160
Minimum Electric Machine Torque (N·m)	-160
Maximum Electric Machine Power (kw)	55
Battery Capacity (A·h)	6.9
Initial State of Charge (-)	0.5

3.5 Signal Collection

In order to carry out the objective drivability assessment, as mentioned in the previous chapter, certain vehicle signals are requested and need to be sent into the AVL-Drive. Most of them can be directly taken out from the simulation results in the GT-Post and several signals have to be developed by some means. All the necessary signals are listed in Table 3.3:

Table 3.3: Requested vehicle signal list

Available Vehicle Signals	*Missing Vehicle Signals*
Vehicle Speed	Accelerator Pedal Position
Longitudinal Acceleration	Brake State
Engine Speed	Brake Pedal Position
Electric Machine Speed	
Electric Machine Torque	
Battery SOC	
Battery Voltage	
Battery Current	
Current Gear Number	

As is shown in the table above, accelerator pedal position, brake state and brake pedal position are the signals which are not available in current model and should be generated indirectly. The corresponding way to produce these missing signals will be explained here:

3.5.1 Accelerator Pedal Position

Accelerator pedal position is a critical signal in the drivability assessment since it stands for the driver's intention of the vehicle dynamic performance. However, due to the diverse power sources, the accelerator pedal position is completely different from the engine pedal position in the hybrid electric vehicle. It is quite understandable that the accelerator pedal position gives the powertrain the level of the requested output torque based on the maximum potential torque at the current condition. The level of the requested output torque can be interpreted as a torque ratio and torque ratio can be calculated by the equations below:

$$T_r = (F_r + m \cdot a) \cdot R \tag{3.3}$$

$$T_{mt} = T_{em} \cdot r_{em} + T_{ice} \cdot r_{ice} \tag{3.4}$$

$$r_t = \frac{T_l}{T_{mt}} \cdot 100\% \tag{3.5}$$

Where T_r is the load torque request, F_r is the total external resistance force, m is the vehicle mass, a is the vehicle longitudinal acceleration, R is the wheel radius, T_{mt} is the maximum theoretical torque at a certain gear combination and vehicle

speed, T_{em} is the maximum electric motor torque at a certain motor speed, T_{ice} is the maximum engine torque at a certain engine speed, r_{em} is the total transmission ratio for the electric motor, r_{ice} is the total transmission ratio for the engine and r_t is the torque ratio.
The maximum theoretical torque indicates the maximum torque the powertrain can send out at current vehicle speed and gear combination. Due to the dual clutch settings, it is possible for engine and electric motor to be engaged through different gear numbers, which leads to fifteen gear combinations in total. All the possible gear combinations and their corresponding maximum theoretical torque are shown in Table 3.4 and Figure 3.9 respectively:

Table 3.4: Possible gear combinations

	ICE 1	ICE 2	ICE 3	ICE 4	ICE 5	ICE 6	ICE 7
EM 2	✓	✓	✓	×	✓	×	✓
EM 4	✓	×	✓	✓	✓	×	✓
EM 6	✓	×	✓	×	✓	✓	✓

"EM 2" means the electric motor is engaged through the second gear and "ICE 1" means the internal combustion engine is engaged through the first gear.

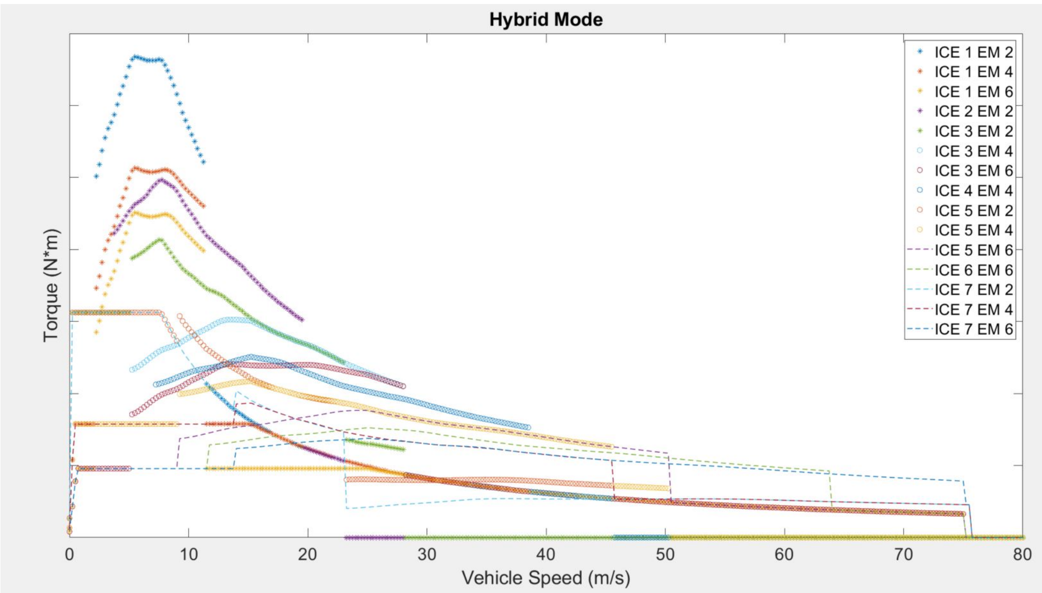

Figure 3.9: Maximum theoretical torque of different gear combinations

The accelerator pedal position is linked with the torque ratio by an accelerator pedal response curve which mathematically describes the relationship between the accelerator pedal position and torque ratio. Normally, the accelerator pedal response curve is supposed to be correlated and derived from the real testing data. However, due to the limited access to the real measurement data as well as the imperfection of the data groups, the pedal response curve can not be accurately verified and therefore three typical pedal response curves are proposed as an assumption:

- **Linear Response Curve**: The accelerator pedal position is directly proportional to the torque ratio.
- **More Responsive Curve**: Compared with the linear pedal response, the powertrain can deliver more torque with the same accelerator pedal position input.
- **Less Responsive Curve**: Compared with the linear pedal response, the powertrain can deliver less torque with the same accelerator pedal position input.

Above three different accelerator pedal response curves are compared and plotted in Figure 3.10 shown below.

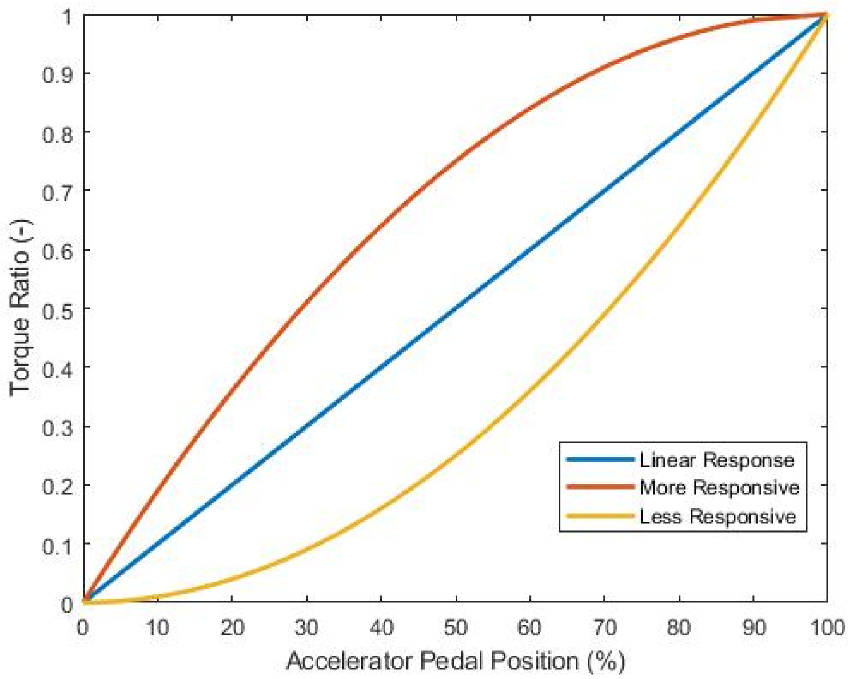

Figure 3.10: Different accelerator pedal response characteristics

3.5.2 Brake State

The brake state indicates if the vehicle is operating a braking maneuver. The standstill and normal braking operations which consist of friction braking and regenerative braking can be regarded as the braking maneuvers and the brake state is equal to one when the braking maneuver is actuated. The principle and method of generating brake state is shown in Figure 3.11 below.

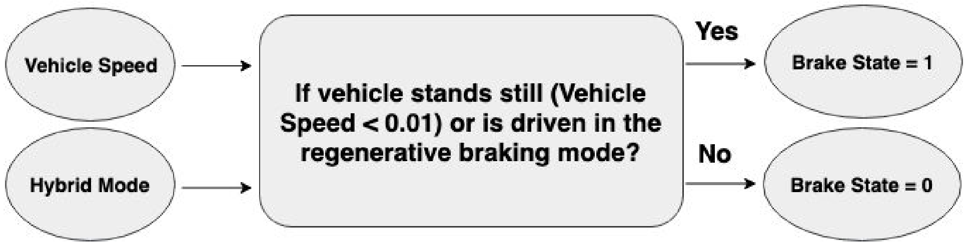

Figure 3.11: Schematic diagram of brake state generation

3.5.3 Brake Pedal Position

The brake pedal position uses the percentage value to measure the level of requested braking torque compared with the maximum braking torque at current condition. When the vehicle is standing still, the brake pedal position is assumed to be one hundred percentage. While during the normal braking operations, the brake pedal position is obtained by having the requested braking torque divided by the maximum braking torque. The maximum braking torque is determined by maximum electric motor torque at current motor speed and the maximum friction braking torque. The related calculation equations and signal generation logic are shown in Figure 3.12 below:

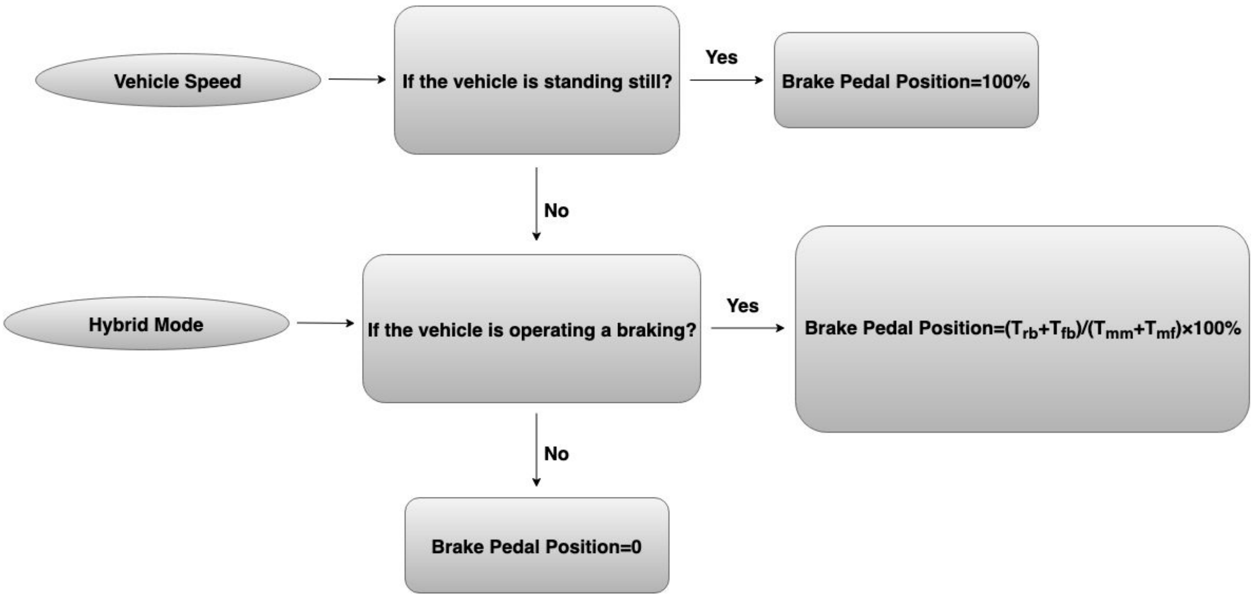

Figure 3.12: Schematic diagram of brake pedal position generation

Where T_{rb} is the requested regenerative braking torque, T_{fb} is the requested friction braking torque, T_{mm} is the maximum electric motor torque at current motor speed and T_{mf} is the maximum friction braking torque.

3.6 Cycle-based Drivability Assessment

In order to conduct objective drivability assessment, AVL-Drive requests a group of vehicle simulation signals as inputs. Cycle-based drivability assessment means the vehicle signals coming from a cycle simulation will be sent to the AVL-Drive for drivability assessment. Since almost all the driving maneuvers will be possible to occur for many times during a driving cycle, with the cycle-based drivability assessment, the operation modes can be covered as much as possible and AVL-Drive will give an average rating of each operation mode to avoid the randnomness. In the later drivability optimization section, all the vehicle signal is collected based on the WLTC cycle simulation. The speed profile of WLTC is shown in Figure 3.13.

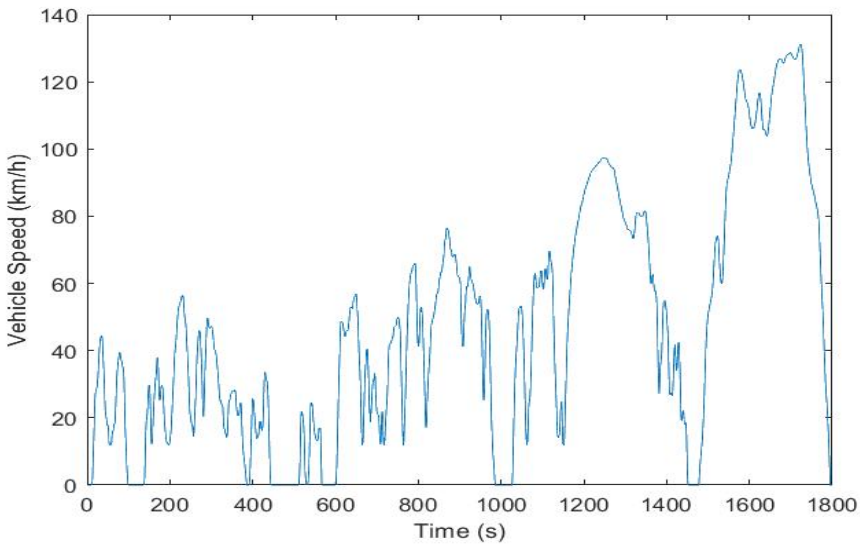

Figure 3.13: Speed profile of WLTC

3.7 Reference Object Construction

To provide the reference objects for drivability comparison, the vehicle signals collected from the driving cycle real testing are needed and sent to the AVL-Drive for drivability assessment. With the help of calibration teams, two groups of real measurement signals from different vehicles are successfully obtained. Based on the measurement signals the drivability is evaluated by AVL-Drive and the assessment results are shown below:

- **Competitor vehicle**: Based on the driving cycle as shown in Figure 3.14, the real measurement vehicle signals of a competitor vehicle are given by the Calibration Team of Geely Powertrain Research Institute and the corresponding drivability assessment results are shown in Figure 3.15:

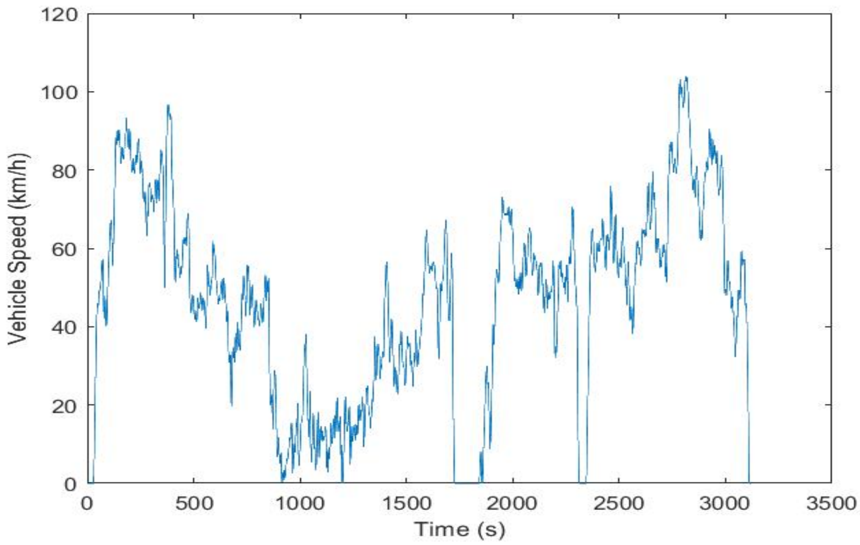

Figure 3.14: Testing driving cycle of a competitor vehicle

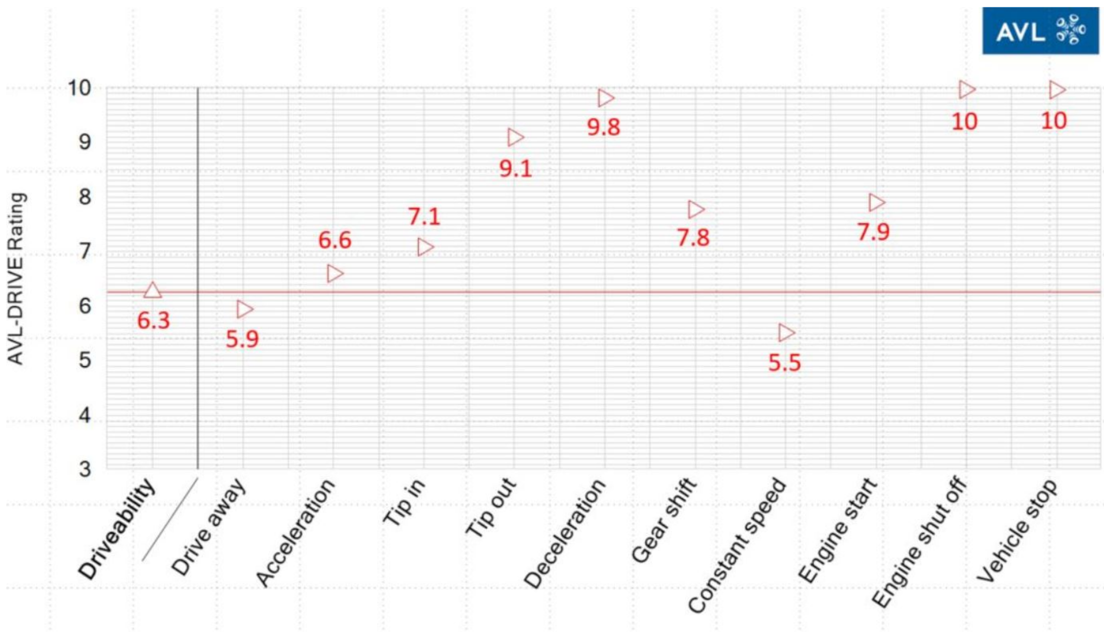

Figure 3.15: Drivability assessment results of a competitor vehicle

- **LYNK&CO 01**: Based on the driving cycle as shown in Figure 3.16, the real measurement vehicle signals of LYNK&CO 01 with a dual clutch transmission are provided by CEVT Calibration Team and the corresponding drivability assessment results are shown in Figure 3.17:

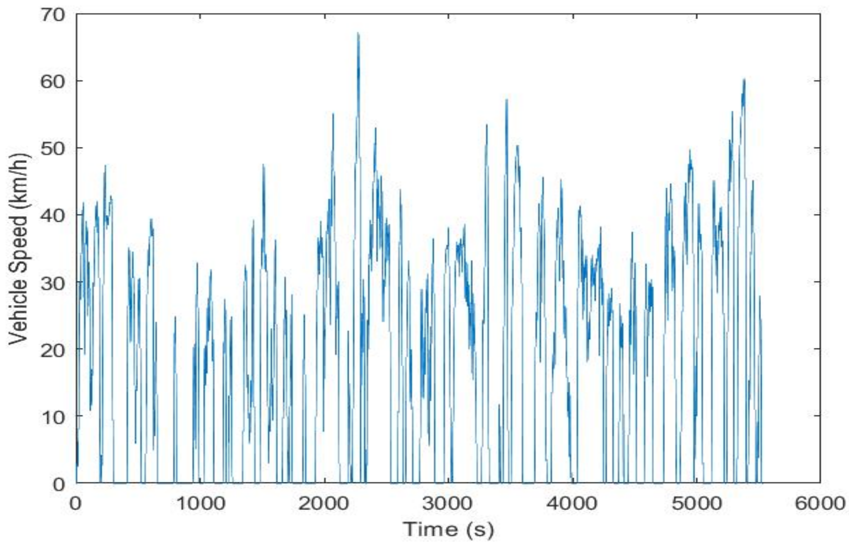

Figure 3.16: Testing driving cycle of LYNK&CO 01

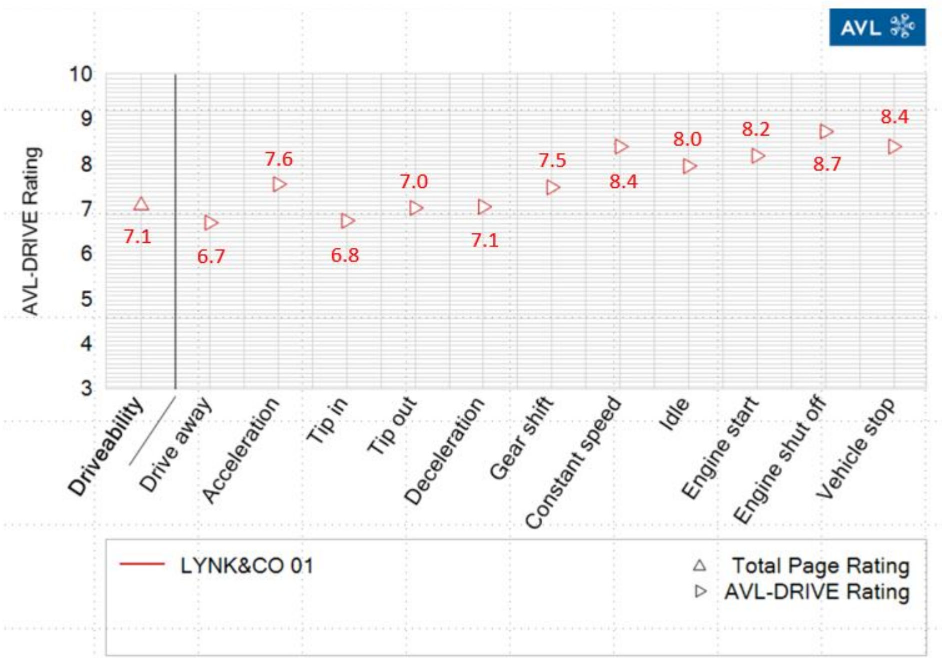

Figure 3.17: Testing driving cycle of LYNK&CO 01

3.8 Targeted Operation Modes

Based on the input vehicle signals and build-in trigger conditions, the AVL-Drive can detect the different driving operation modes and each operation mode is granted a corresponding weight factor which indicates the level of importance when determining the overall drivability rating. The weight factor ranges from 1 to 5 and 5 is the highest weight factor.

Table 3.5: Available operation modes in AVL-Drive

Operation Modes	*Weight Factors*
Drive away	3
Acceleration	3
Tip in	2
Tip out	3
Deceleration	2
Gear shift	4
Constant speed	2
Engine start	3
Engine shut off	1
Vehicle stop	1

Table 3.5 below shows all the operation modes the AVL-Drive can detect and their corresponding weight factors. Due to the limited time, it is not feasible and practical to investigate and optimize the drivability of all operation modes. So, in this project, several critical operation modes will be figured out and selected as the objects for drivability optimization. The engine start and gear shift are considered as the targeted operation modes for drivability optimization because of the reasons shown below:

- **Engine start**: Engine start tends to be actuated more frequently in the hybrid electric vehicle because of the mode switch and the engine start will always occur during the other operation modes such as drive away, acceleration and tip in. The drivability of these related operation modes can be improved indirectly by optimizing the drivability of engine start.
- **Gear shift**: According to Table 3.5, the gear shift has been granted the highest weight factor, which means the gear shift is regarded as the most important operation mode by AVL-Drive. It is discovered that the gear shift will also occur frequently during the other operation modes such as acceleration, tip in, tip out and deceleration. Similarly, the drivability of these related operation

modes can be improved indirectly as well by achieving a better drivability performance of gear shift.

4

Results

In this chapter, the generation results of missing vehicle signals will be shown. The model deficiency in terms of the drivability of engine start and gear shift will be pointed out and the drivability result comparison of engine start and gear shift between the original model and optimized model will be clarified as well. The optimization result of overall drivability will also be included.

4.1 Signal Generation

In the methodology section, the signal generation methods of brake state, brake pedal position and accelerator pedal position, the missing signals, are introduced and explained. The following subsections will show the profile of these signals coming from a cycle simulation.

4.1.1 Brake State

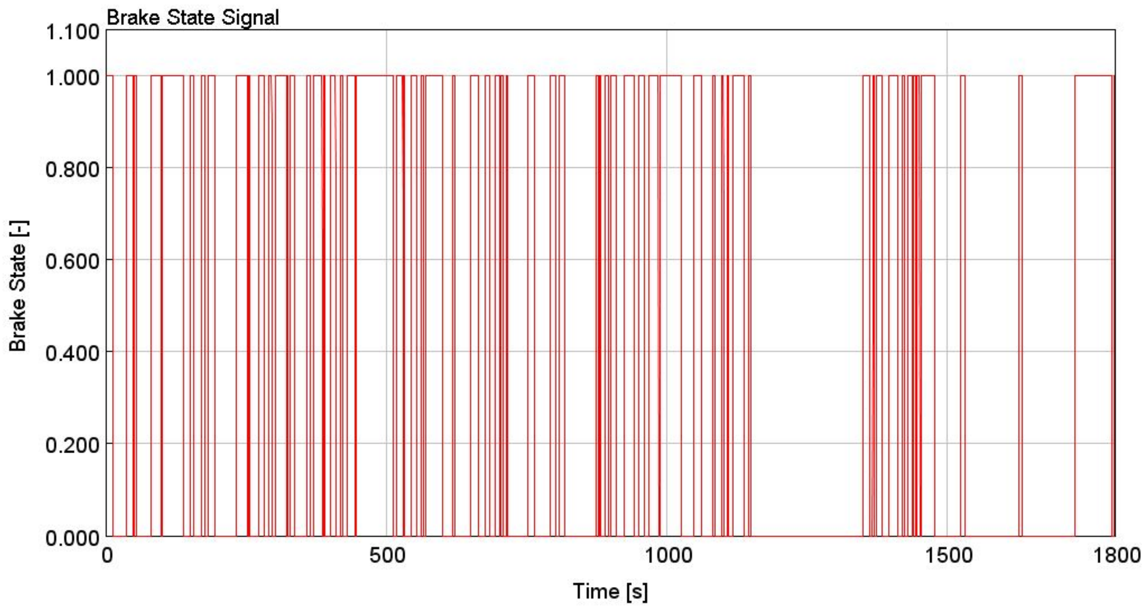

Figure 4.1: Brake state signal

The signal of brake state has been developed successfully according to the generation logic and it's profile is shown in Figure 4.1. It can be clearly observed that the brake state is switching between 0 and 1 as expected. If the brake state is equal to 1 the vehicle is running in a braking operation and if the brake state is equal to 0 the vehicle is moving forward without the braking operation.

4.1.2 Brake Pedal Position

The signal of brake pedal position has been generated and its profile is shown in Figure 4.2. Compared with the signal profile of brake state, the brake pedal position is equal to zero if there is no braking operations (Brake State = 0) and the brake pedal position is a nonzero value if the braking operation is actuated (Brake State = 1).

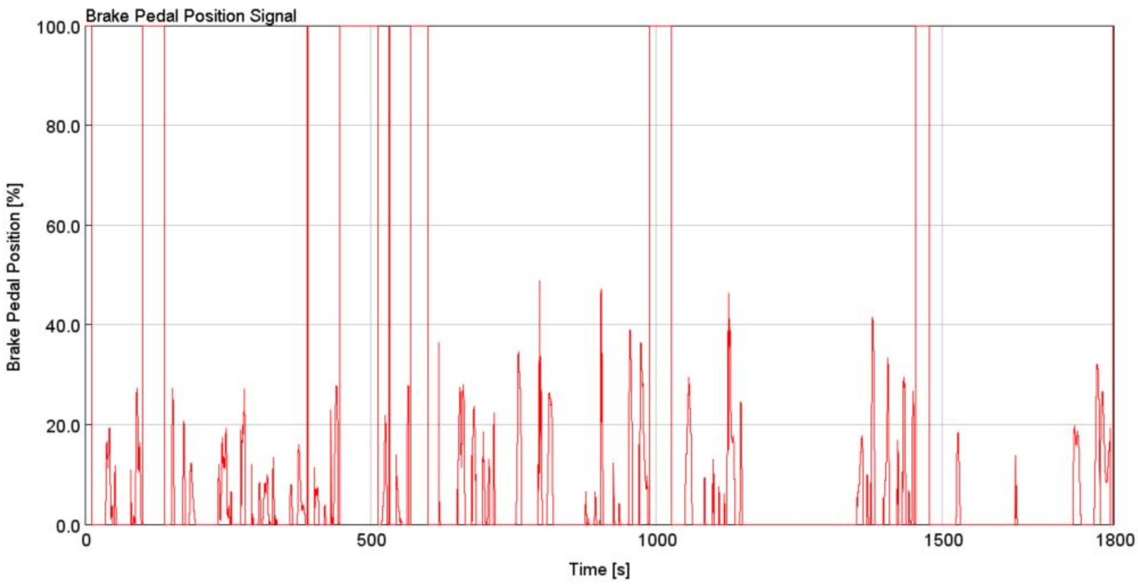

Figure 4.2: Brake pedal position signal

4.1.3 Accelerator Pedal Position

The signals of accelerator pedal position with three different pedal response settings are shown in Figure 4.3. It can be obviously found out that these three signal profiles actually follow the same trend and they differentiate themselves only by value amplitude. At each time point, compared with the linear pedal response, a more responsive pedal enables a smaller pedal position to achieve the same level of output torque and a less responsive pedal needs a larger pedal position to deliver the same level of output torque.

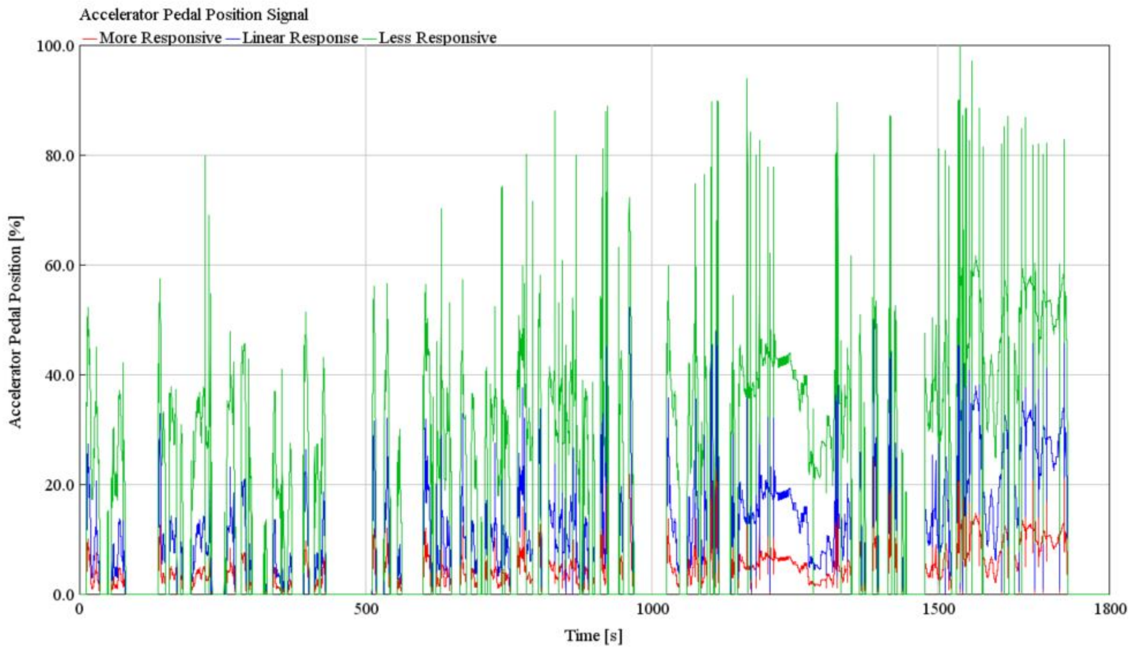

Figure 4.3: Accelerator pedal position signal

4.2 Engine Start Optimizaion

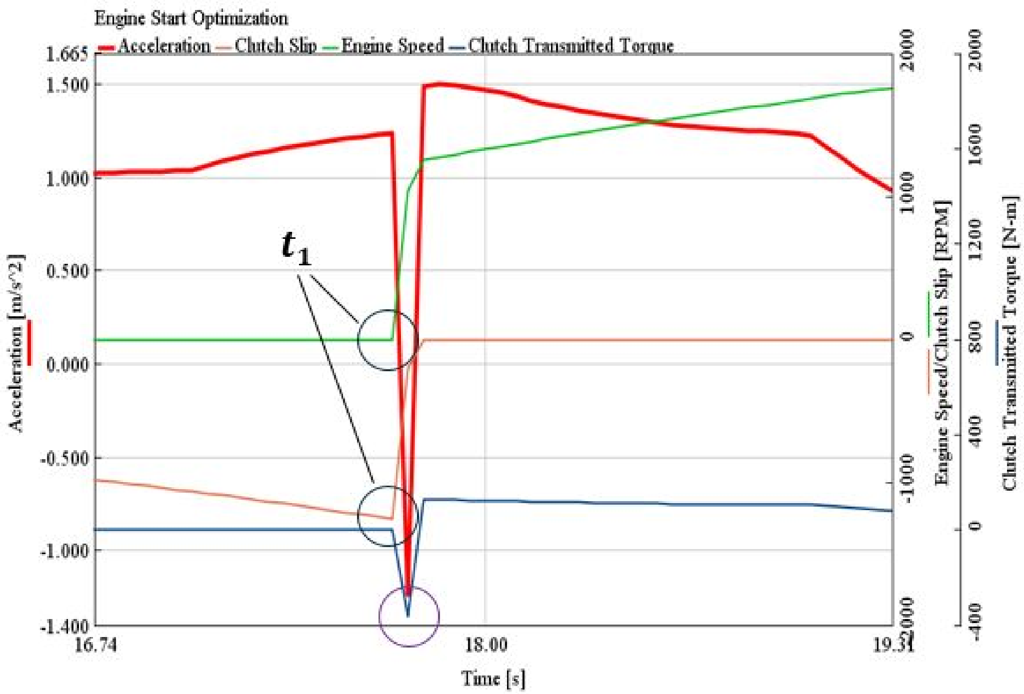

Figure 4.4: Acceleration profile of original model during the engine start

During the engine start, the engine is engaged through the either odd clutch or even clutch and the engine speed goes up from zero to a certain speed. A huge instantaneous deceleration can be spotted during the engine start as shown in Figure 4.4. The engine actually begins engaging at the t_1 point as marked by the black circles. At this time point, the engine speed is almost equal to zero and the clutch slip is around -1200 RPM. According to the equation of clutch slip shown below, the rotating speed of clutch output shaft can be calcualted and is equal to 1200 RPM roughly.

$$w_e = w_{ci} \tag{4.1}$$

$$w_{cs} = w_{ci} - w_{co} \tag{4.2}$$

Where w_e is the engine speed, w_{ci} is the rotating speed of clutch input shaft, w_{co} is the rotating speed of clutch output shaft and w_{cs} is the clutch slip.

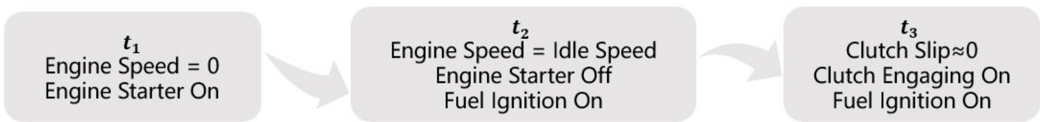

Figure 4.5: Three time phases of engine start

It is understandable that when the stationary engine shaft suddenly contacts the fast rotating clutch output shaft at t_1 point, in order to shrink the clutch slip, the rotating shaft will accelerate the engine shaft as fast as possible by applying a huge positive torque. In return, the engine shaft will resist the clutch output shaft by providing a huge negative torque. Then this huge negative torque will be transmitted through the transmission system to the vehicle wheels and decelerates the vehicle finally. In order to improve the drivability of engine start, the acceleration profile can be smoothed by enabling a small clutch slip when engaging the clutch which will eliminate the huge instantaneous clutch transmitted torque during the engine start. Figure 4.5 demonstrates the procedures of achieving a small clutch slip by dividing the engine start into three time phases.

Figure 4.6 shows the engine start process in the optimized model, which has taken the clutch slip into account. As three time phases mentioned above, From t_1 to t_2, the engine will be cranked by a motor starter and the engine speed will go up from zero the idle speed. After that, from t_2 to t_3, the motor starter is off and by fuel ignition the engine speed will continue to go up from idle speed to a certain speed level which can achieve a minimum clutch slip. During the whole process, the electric machine will be responsible for maintaining the traction force. In the optimized model, the clutch will actually be engaged at the t_3 instead of t_1 in the original model. Since the clutch is engaged with a small clutch slip, the huge deceleration spike has disappeared.

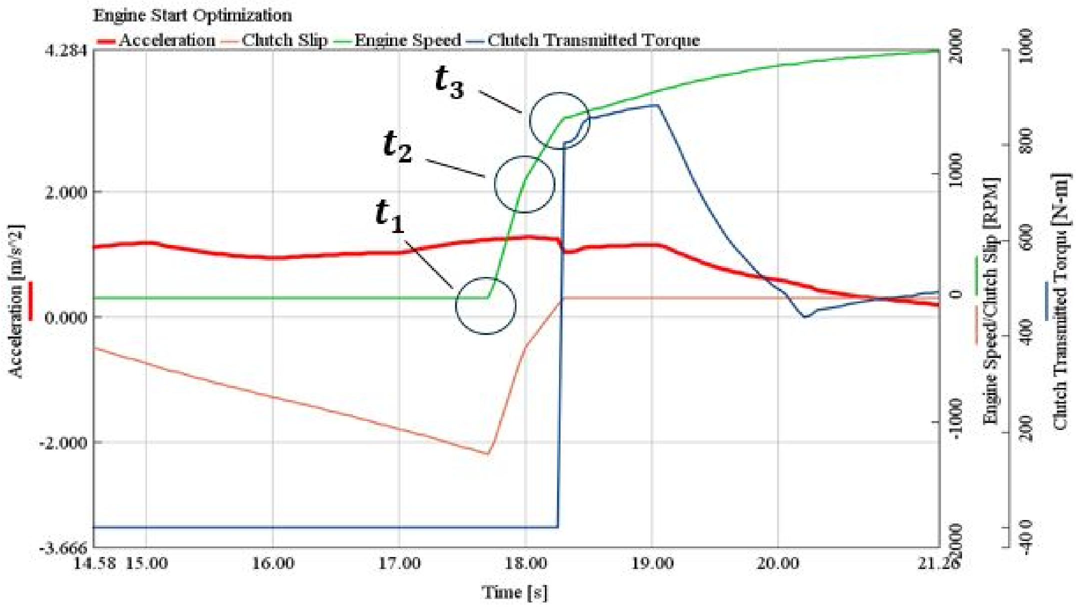

Figure 4.6: Acceleration profile of optimized model during the engine start

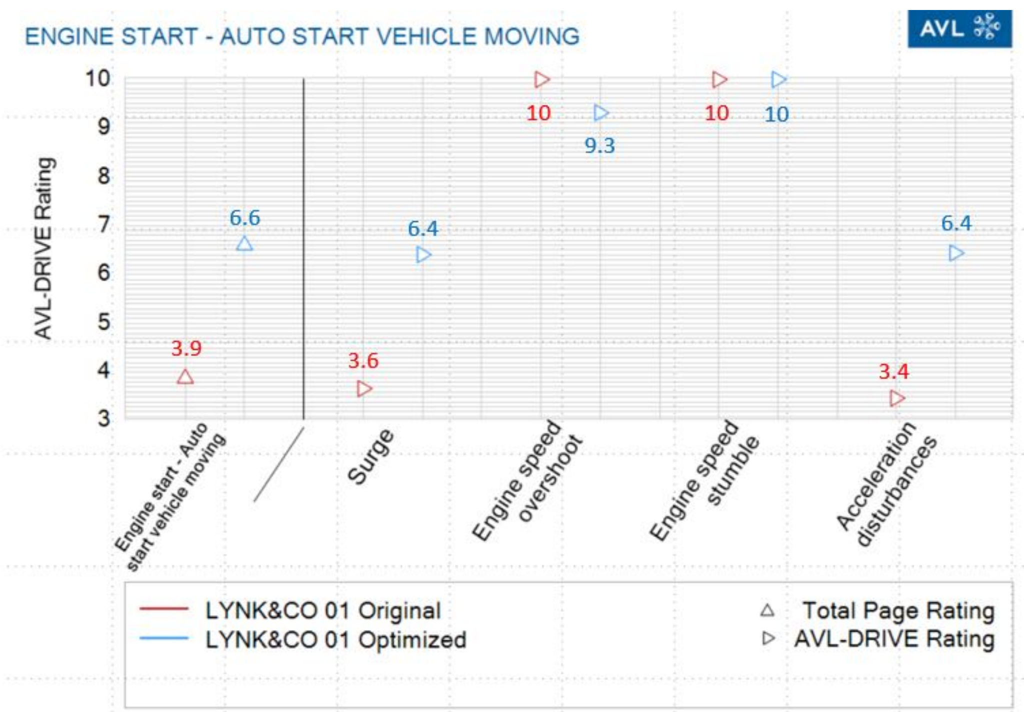

Figure 4.7: Drivability rating comparison of engine start

In terms of the engine start, the drivability rating comparison between the original model and optimized model is shown in Figure 4.7. With a smooth acceleration profile, the drivability ratings of surge and acceleration disturbances, these acceleration-related criteria, have been improved hugely. Due to the higher ratings of criteria, the drivability rating of engine start has also been raised up accordingly.

4.3 Gear Shift Optimization

The gear shift is a frequent driving maneuver and involves the both disengagement and engagement of the clutches. For instance, during the engine upshift from the second gear to the third gear, the even clutch will be disengaged firstly and then the odd clutch will be engaged through the third gear. In this gear shift optimization part, the power-on upshift from the second gear to the third gear is the main investigation and optimization target.

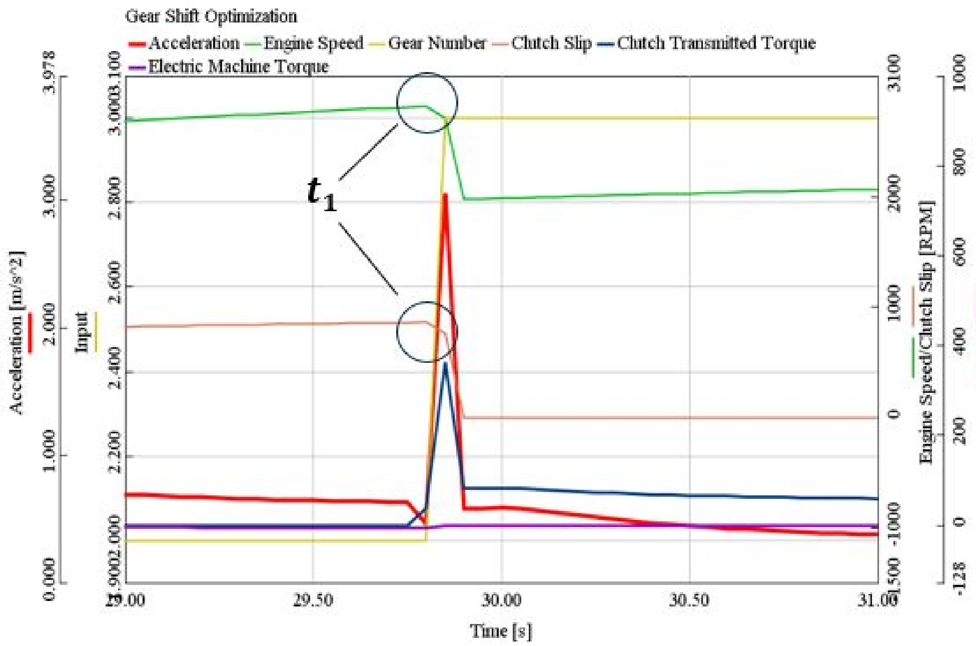

Figure 4.8: Acceleration profile of the original model during the gear shift

Figure 4.8 displays the acceleration profile of the original model during the gear shift. As shown in this figure, a huge instantaneous acceleration spike can be seen and the causation of this acceleration bump has almost the same principle introduced in the section of engine start optimization. At t_1, the beginning time point of the gear shift, the engine shaft is spinning with a certain rotating speed and the clutch slip is a large positive value which means the engine shaft rotates quite faster tham the clutch output shaft according to the calculation equation of the clutch slip. In this case, the engine shaft will accelerate the clutch output shaft as fast as possible by applying a huge instantaneous positive torque in order to shrink the speed difference. This huge positive torque will be transmitted through the transmission system to the vehicle wheels and accelerate the vehicle finally.

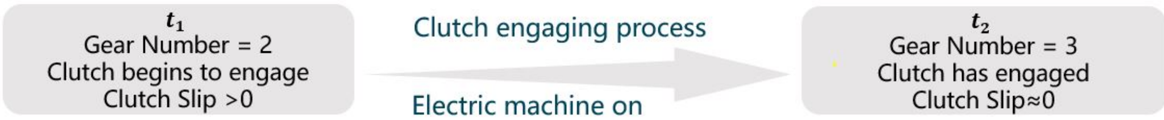

Figure 4.9: Two time phases of the gear shift

To improve the drivability of gear shift, the acceleration spike should be mitigated. Similarly, if a small clutch slip can be achieved when clutch engagement begins, the acceleration spik will also be smoothed. However, with a positive clutch slip at the beginning, the engine speed should go down to a certain level by some means. Several different solutions of decreasing the engine speed such as cutting off the fuel supply have been implemented in the model but none of them delivered the expected performance. Since the root reason for the acceleration spike is the clutch transmits much more torque than requested and consequently the torque balance will be broken. So commanding electric machine to absorb the extra torque transmitted by the clutch could also be a reasonable and feasible solution. In order to give a clear picture of gear shift process, the two time phases are introduced in Figure 4.9.

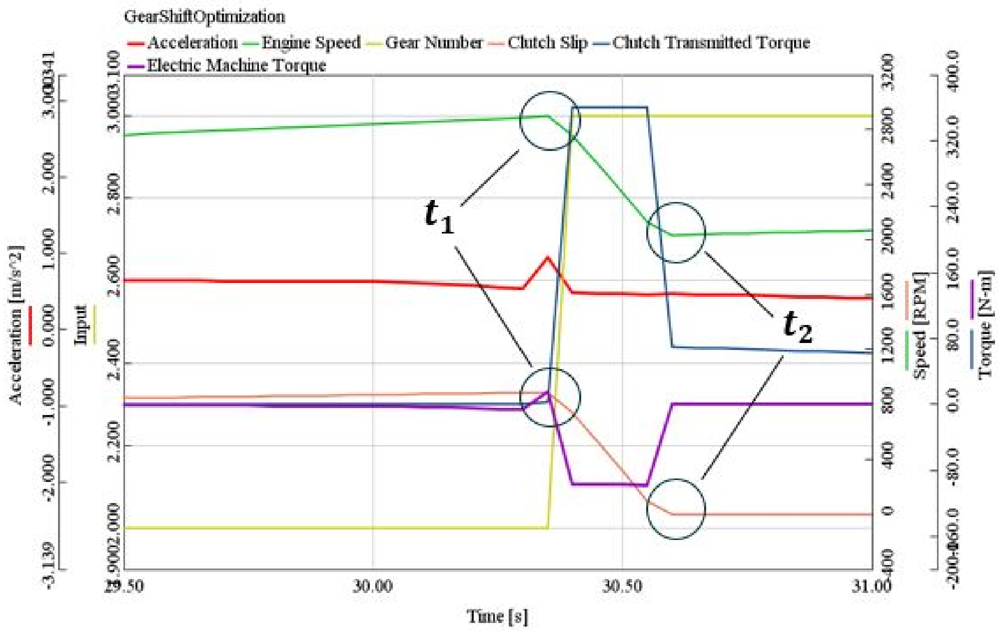

Figure 4.10: Acceleration profile of the optimized model during the gear shift

As shown in Figure 4.10, the acceleration spike during the gear shift has been mitigated significantly. At the t_1 the clutch begins engaging with a large positive clutch slip and at the same time the electric machine also starts delivering the negative torque to consume the extra torque transmitted by the clutch. In order to achieve a torque balance, the electric machine torque should be controlled according to the equation shown below:

$$T_{em} = \frac{T_r - T_c}{r_{em}} \tag{4.3}$$

Where T_{em} is the electric machine torque, T_r is the requested traction torque, T_c is the clutch transmitted torque and r_{em} is the gear ratio for electric machine.

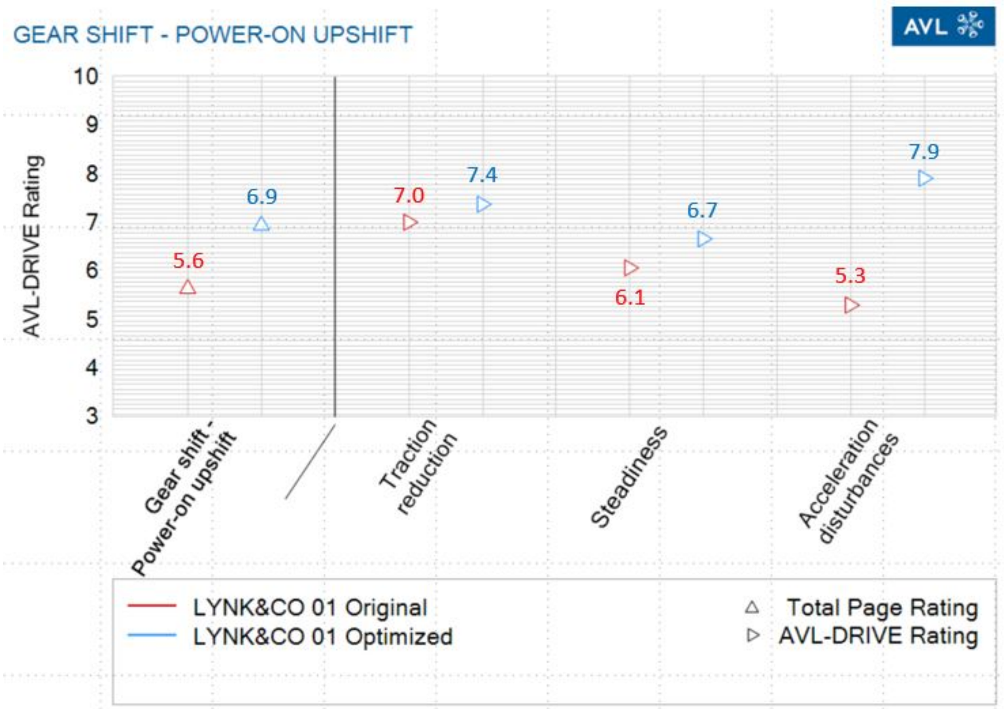

Figure 4.11: Drivability rating comparison of gear shift

Since during the gear shift the electric machine is actually working as a generator to consume the surplus clutch transmitted torque, the torque balance can be achieved and the acceleration spike has been smoothed dramatically. It can be observed from Figure 4.11 the rating of acceleration disturbance which is highly related with the smoothness of the acceleration profile has been improved significantly. Because of the higher ratings of criteria, the drivability rating of gear shift has been raised up accordingly.

4.4 Drivability Optimization Overview

Based on the vehicle signals of WLTC cycle simulation in the original model, the drivability is evaluated by AVL-Drive and an overview of drivability assessment results with three different pedal response implementations is shown in Figure 4.12. In these three cases, the total AVL-Drive ratings are all located between 4 and 5 which are unacceptable according to the rating system. The drivability rating of engine start is the lowest among all the operation modes and one of the most critical limitation for the total AVL-Drive rating. It can be found out that the original model has a relatively good drivability in deceleration, tip out and constant speed. By comparing the drivability ratings of each operation modes with different pedal response characteristics, the influence of accelerator pedal response on drivability results can be obviously discovered in the tip in and tip out since the detection and evaluation criteria of these operation modes are highly related with the profile of the accelerator pedal position.

OVERVIEW

Operation Modes	Original More Responsive	Original Linear Response	Original Less Responsive
	DR	DR	DR
AVL-DRIVE Rating	4.8	4.7	4.9
Drive away	6.0	5.4	5.9
Acceleration	5.0	4.9	5.3
Tip in	5.4	5.7	5.8
Tip out	7.1	8.7	6.7
Deceleration	7.5	7.5	7.5
Gear shift	5.6	5.5	5.5
Constant speed	9.8	9.9	9.9
Engine start	3.9	3.8	4.0
Engine shut off	5.7	5.7	5.7

Figure 4.12: Drivability rating overview of original model

Figure 4.13 shows an overview of drivability assessment results of optimized model with three different pedal response implementations. In these three cases, the total AVL-Drive ratings are all located between 6 and 7 which are acceptable according to the rating system. Compared with the drivability overview of the original model shown above, it can be spotted that the drivability ratings of engine start and gear shift have been improved. Due to the improved drivability ratings of engine start and gear shift, the drivability ratings of drive away, acceleration and tip in have also been raised up indirectly as expected. The drivability rating of drive away tends to be influenced by the pedal response characteristics as well.

OVERVIEW

Operation Modes	Optimized More Responsive	Optimized Linear Response	Optimized Less Responsive
	DR	DR	DR
AVL-DRIVE Rating	6.4	6.3	6.3
Drive away	7.4	5.9	6.0
Acceleration	6.1	6.3	6.3
Tip in	6.4	6.6	6.5
Tip out	8.3	8.5	6.9
Deceleration	7.1	7.0	7.0
Gear shift	6.1	6.0	6.0
Constant speed	9.6	9.9	9.9
Engine start	6.9	7.0	7.0
Engine shut off	5.8	5.8	5.8

Figure 4.13: Drivability rating overview of optimized model

5
Conclusion

In this chapter, the whole thesis project will be concluded and based on all the findings a brief summary will be delivered. By combining the limitations and deficiencies, some possible directions of perfecting the thesis project are proposed in the future work.

5.1 Summary

In this thesis project, a LYNK&CO 01 hybrid electric vehicle is modelled in the GT-Suite and based on the vehicle simulation signals the drivability is evaluated objectively by AVL-Drive. The engine start and gear shift, two critical operation modes, are selected as the optimization objects and investigated respectively. In order to improve the drivability, the corresponding modifications have been applied on the vehicle model. Concretely, the project can be concluded from the following respects:

- **Signal Identification and Generation**: All the necessary vehicle signals for drivability assessment in AVL-Drive have been identified. The brake state, brake pedal position and accelerator pedal position, three missing vehicle signals, have been generated successfully. In terms of the signal generation of the accelerator pedal position, the pedal response curve is critical and determines the signal amplitude.
- **Tool and Signal Connections**: The vehicle simulation signals coming from the GT-Suite can be transported to the AVL-Drive with the help of Matlab. The Matlab functions as a temporary signal keeper and saves the vehicle simulation signals as the format which can be recognized by AVL-Drive.
- **Virtual Drivability Evaluation and Optimization**: It has been proved feasible and practical to have access to the virtual drivability assessment at the early concept stage by connecting the GT-Suite with AVL-Drive. The cycle-based assessment method has been implemented to evaluate the drivability of targeted vehicle and reference vehicles. Regarding the drivability optimization, the drivability ratings of engine start and gear shift have been improved

significantly by smoothing the acceleration profile and the drivability ratings of tip in and tip out are more sensitive to the pedal response characteristics.

5.2 Future Work

Due to the limited time and conditions, this thesis project is conducted with certain simplifications and assumptions. In order to perfect the thesis work and deliver more reliable results, there are several points which should be taken into account and further investigated:

- **Road Profile**: The road is assumed to be completely flat with zero road gradient in this thesis project. In order to generate more accurate and realistic vehicle simulation signals, a more complex road profile needs to be defined.
- **Inertia Settings**: The accurate inertia values of rotating components should be figured out and applied in the vehicle model to deliver more reliable vehicle simulation results.
- **Force-actuated Synchronizer Model**: The drivability optimization on gear shift can be further carried out with an implementation of force-actuated synchronizer model.
- **Pedal Response Verification**: In this thesis project, three possible pedal response curves have been proposed and also implemented in the vehicle model for drivability assessment. To determine the correct pedal response characteristics, the related real measurement vehicle signals should be collected and used for pedal response verification.
- **Vehicle Attribute Compromise**: In order to achieve an optimal design, it is fairly necessary to investigate the relationship between the drivability and the other critical vehicle attributes such as fuel consumption and emission performance. These vehicle attributes should also be taken into account during the drivability optimization.

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