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# Model Exchange for Virtual SIL/MIL Verification of Passenger Cars with Electric Axles

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## Abstract

In the present day, stiff competition in the automotive industry and shorter timelines for introduction of new passenger vehicles has forced vehicle manufacturers and component suppliers to cut down on development time. Virtual simulations help in bringing down this time drastically and are a critical phase in the design and development of new vehicles. Multiple subsystems make up a vehicle and these subsystems need to be tested before being used in production. In the case of system development in electric vehicles, virtual verification of subsystems early in the project phase is important given the platform modularity of the driveline in such a scenario. It also helps if the simulation models are modular, since model exchange between vehicle manufacturer and subsystem suppliers have to take place to build virtual prototypes. This report explores the modelling and simulation of such type of modular drivetrain for electric passenger vehicles. The modelling of drive axle as a subsystem is a key aspect in this project. Three types of drive axles, i.e., Torque Vectoring Dual Clutch (TVDC), Electric Torque Vectoring (e-TV) and an Open Differential axles are considered. Modelling the powertrain, specifically the motor, is done to determine the energy consumption of this driveline. Modelica language uses an equation-based modelling approach which has a higher flexibility when compared to the library-based modelling. For this reason, the open-differential model was modelled in Modelica and was exported as a Functional Mock-up Unit (FMU). The TVDC model and the e-TV model is given as inputs by the concerned stakeholders from the project. Further, these models were integrated with a control model and a vehicle model in a virtual verification environment, namely, IPG CarMaker. To establish a comparison between these different models, vehicle performance and energy consumption of these drivelines were studied.

Validation and verification of the developed models were carried out as a precursor to simulation in the project. Sanity check of the model was done to make sure that the given vehicle does not run off the desired path. This ticks off the basic physics involved in the models. This was an iterative process based on the validation results of the models. Further, to draw a comparison between the different powertrains, the models were simulated with an open diff at the rear wheel (RWD) as a reference. Plots for dynamic variables and energy were used to analyze the results and compute measures like vehicle performance and energy consumption.

AWD, as expected, performed the best in terms of vehicle stability. However, the interesting comparison was between e-TV and the TVDC models. To establish a comparison for the RWD configurations, the open differential at the rear axle is taken as a reference. Apart from the deduced results, the most relevant aspect of the project, i.e., the modularity of the subsystems (specifically, the drive axles) was achieved.

**Keywords:** Vehicle Dynamics, Torque Vectoring, Modelling, Simulation, Energy Consumption, TVDC, e-TV, Open Differential, All-Wheel Drive, Rear-Wheel Drive, FMU, Dymola, CarMaker, Matlab, Simulink

## Abbreviations

AWD	All Wheel Drive
RWD	Rear Wheel Drive
BEV	Battery Electric Vehicle
TVDC	Torque Vectoring Dual Clutch
e-TV	Electronic Torque Vectoring
FMU	Functional Mock-up Unit
FMI	Functional Mock-up Interface
OTD	Optimal Torque Distribution
BW	BorgWarner
CM	CarMaker
PT	Powertrain
VVE	Virtual Vehicle Environment

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# 1 Introduction

## 1.1 Background

Rapid electrification of passenger vehicles has lead to manufacturers focusing on shorter lead times for development due to stiff competition in the market. Virtual simulations help bring down this development time and hence, is a key step in any new project.

In the case of system development, subsystems need to be verified at an early stage. This should be done in two stages, one, testing at individual level and, two, validation at complete vehicle level. During the second stage, there is a need that these subsystems have to be exchanged to arrive at the best possible solution. In this project, we focus on one such subsystem, the drive axle.

## 1.2 Problem Statement

Virtual verification of subsystems, in this case, drive axles is a broad perspective of this project. Modular axles have to be built and tested out in a virtual environment. This can be summarized into two major tasks:

1. **Build** a modular drivetrain library for passenger cars with e-axles
2. **Compare** the different e-axle **configurations** by analyzing the
  - Vehicle dynamic stability and performance
  - Energy consumption

## 1.3 Objective

To **develop** and **test** different **combinations of subsystems** (specifically, drive axles) for a given vehicle model in a **virtual test environment**.

## 1.4 Deliverables

1. Libraries for subsystems, specifically modular drive axles
2. CarMaker models with environment for virtual verification
3. Verification of the above deliverables works' through some case studies

## 1.5 Limitations

The powertrain architectures modelled in this project are of BEV type. BEV or Battery Electric Vehicles are vehicles that run entirely on electricity. In other words, one or more electric motor along with a battery supply the power to the wheels [1]. BEV can have different architectures. The majority of them have the motor on the front axle coupled with a gearbox with the battery being mounted on the floor. Some of them have however two motors, one being mounted on the front axle and on the rear axle, which gives the vehicle all-wheel drive capabilities [2].

## 1.6 Assumptions

In order to address the scope and achieve the desired results in a given time-frame, several assumptions have been made. Examples of such are:

- The center of gravity is same for all configurations despite the differences in build structure
- The small motor used for e-TV has constant efficiency whereas the main prime mover i.e., the propulsion motor has an efficiency map
- Losses were considered for motors and not elsewhere, otherwise mentioned for a particular model.
- Friction  $\mu$  is considered to be 1 on dry asphalt to simulate the best grip conditions
- The track used for simulation is free of bumps, potholes and is always dry

## 2 Theory

### 2.1 Literature Study

A literature study about BEV architectures, differentials and torque vectoring systems was done. Familiarity with the software used in this project, like CarMaker, Modelica and Simulink was also crucial since all of the work would be carried out on these said tools.

Most electric vehicles have a battery, which supplies energy to a motor. The motor then transfers the power to a mechanical transmission which in turn transfers the power to the wheels via a distribution transmission, e.g. an open differential, an electronic differential or a Torque Vectoring Dual Clutch (TVDC) system. Torque vectoring is a control system that basically allows moving the torque from the left wheels to the right wheels and vice versa. In vehicles without torque vectoring, i.e., only an open differential, equal torque is distributed to left and right wheel. In other words, if a wheel on one side is slipping, the torque will still go to that wheel, making it hard for the vehicle to move out from the slippery situation. To prevent that, torque vectoring transfers the power to the side that has the most traction, which is beneficial in slippery situations. Furthermore, this system allows a vehicle to steer faster through a corner by sending the power to the outer wheel. This improves the handling of the vehicle.

### 2.2 TVDC System

A TVDC system shown in figure 1 is a conventional differential that uses clutches on both sides of the wheels, sitting on the axle, to distribute the torque. When the vehicle is around a corner torque needs to be on the outer wheel, the clutches on that side would be fully engaged and partially on the inner wheel. will be active and they will work to either increase or reduce the torque pointed to a wheel. The amount of torque needed is dictated by the level of clutch engagement [3].

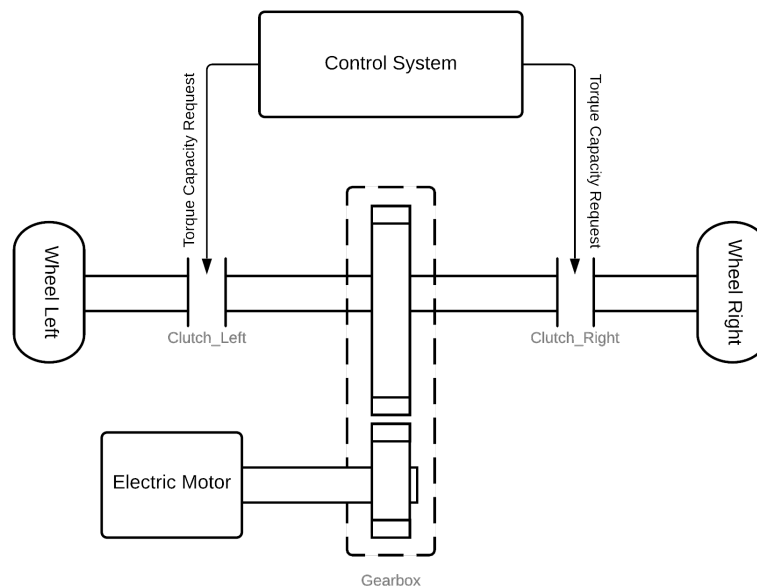


Figure 1: Schematic of the TVDC system ([3])

When the clutches are fully engaged (while propelling forwards) the TVDC functions as a conventional rotary rigid axle. In driving scenarios such as driving through a large corner, the system increases the stability and handling of the vehicle going through the corner by increasing the amount of torque being sent to the outside wheel. This increases the yaw effect, in other words, it allows the car to rotate more easily through a corner thus a more responsive and precise cornering is achieved ([4]).

The TVDC system was provided BorgWarner (BW), however the model of it was given by Volvo. The system includes a propulsion motor coupled to a two-speed gearbox that sends the power to the left and right wheel.

### 2.3 e-TV System

The e-diff system that is shown in figure 2 and used in the modelling is provided by BW [5]. This system also uses a propulsion motor that sends the power to the wheels via a gearbox, but achieves the torque vectoring function by using a small electric motor coupled to a reducer gear that is connected to the differential instead of using clutches. When one of the wheels on either side needs extra torque, that motor will supply it. The schematic of this system is shown in the figure below.

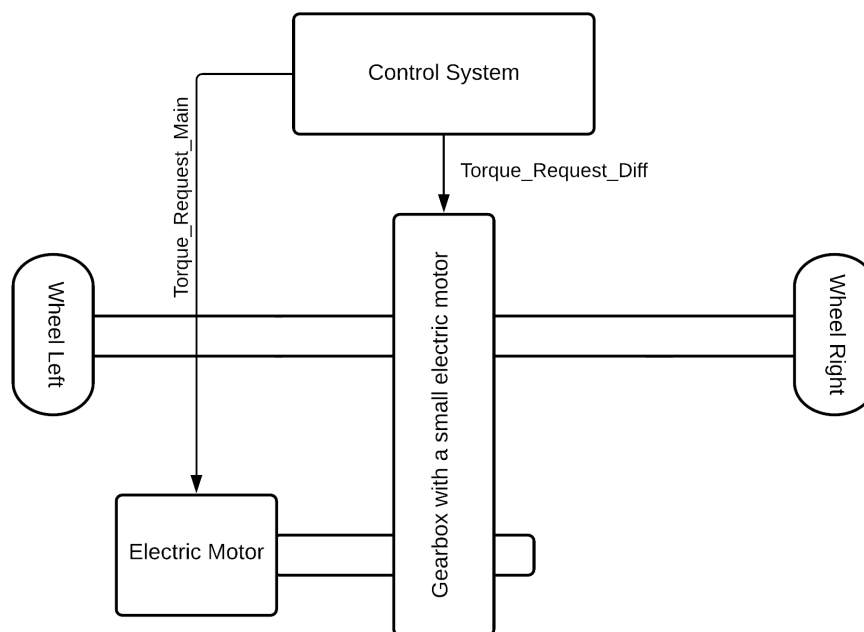


Figure 2: Schematic of the e-TV

Compared to the TVDC system, the eTV improves the torque vectoring function by delivering high efficient and precise needed torque to the wheel as well as being able to apply negative torque on a specific wheel. Also, electric motors have the ability to quickly vary the torque supplied to the needing wheel so that the vehicle responds instantly to inputs from the control system or the driver.

## 2.4 Vehicle Dynamics & Energy Consumption

The next step was to determine which variables to be studied, in order to analyze the different configurations' dynamics and energy efficiency, and compare them between each other.

- The torque at each wheel is an essential parameters to be studied as it shows how it's being distributed between the front and rear axle and left and rear side, depending on if the configuration is an AWD one or a RWD one. The key to why it's important to study the torque distribution is to see how the torque vectoring system is dividing the torque between the left and right side, specially in corners.
- Steering angle  $\delta_f$  is another essential parameter to be studied as it will indicate how much input is needed by the driver for the vehicle to navigate through a specific corner, allowing for the analysis of the vehicle response. It is defined by the angle of which the driver rotates the steering wheel which in its turn determine the turning radius of the vehicle. It is defined and calculated by the equation below:

$$\delta_f = \frac{L}{R_p} + K_u \cdot \frac{m \cdot v_x^2}{R_p} \quad (1)$$

where  $L$  is the wheelbase length and  $R_p$  being the turning radius.

- Lateral acceleration  $a_y$  acts laterally to the car. It is noticeable, for instance, when driving through a bend as a centrifugal force towards the outside of the bend. It is important to study this parameter as it predicts the vehicle behaviour in terms of cornering capability and sheds light into the performance of the torque vectoring system.
- Lateral deceleration is usually observed when the vehicle's velocity is decreasing for example when braking.
- Yaw angle is basically the angle between where the vehicle is pointing and where the vehicle is actually travelling. It also indicates how the vehicle is responding to the steering input.
- Yaw rate  $\omega_z$ , is the angular velocity of the vehicle's rotation or the rate of rotation of the vehicle around its vertical axis. It needs to be studied because it gives valuable information about the torque vectoring system's behaviour in corners and torque distribution since different distributions result in different moments acting on the vehicle, thus affecting the yaw rate [6].
- Longitudinal slip angle of the tire is defined as the difference between the speed of the axle relative to the road and the tire tangential speed. It is a crucial parameter to be studied, as it indicates how efficient the applied longitudinal and lateral forces are. It is also important for the torque vectoring system as it uses its value to detect any slip and correct in time [7].
- Side slip angle of the tire is defined as the difference angle of where the tire is pointing and where it's actually travelling. Generally the higher the slip angle is the less grip a tires has. This parameter is crucial because it shows how stable he vehicle is, like if it's losing grip, understeering or oversteering [8].
- Energy consumption of the vehicle is the amount of energy or power used on a specific track. This is the main variable to be studied when comparing the efficiency of the model configurations as it predicts how good the torque vectoring systems are at drawing a minimal amount of energy from the batteries.

### 3 Modelling

Modular AWD e-axle drivelines was the key property considered while modelling the propulsion subsystem. It was selected to follow the modularity defined in the CarMaker OpenXWD-Standalone environment. Within this propulsion module, there are sub-modules, e.g. the Open-Differential. The Open-Differential was modelled in the Modelica format with tool Dymola using equations. As it is acausal modelling having better integration of physical domains depicting better parameterization and functionality. Existing stakeholder's eTV and motor Simulink models were re-modelled to adapt Car Maker input/output interface. Modelica based Open differential exported to Simulink as functional mock-up unit (FMU)[3] was integrated with e-axle modular architectures then integrated to CarMaker full vehicle environment. TVDC Modelica based FMU and control logic (Simulink based) provided by stakeholders was used as they were functional and compatible to emphasis on building multiple e-axle architectures. The generic AWD e-axle architecture gives the user flexibility to derive many vehicle configurations varying the modular driveline. The modules Open Differential, TVDC and eTV can be used as either front axle or rear axle as depicted in the figure 3. There are possibilities to model a Rear wheel driven vehicle removing the front wheel driveline. Propulsion motors can also be varied from dual motors to quad-motors or to the user requirements with the same vehicle model and driveline.

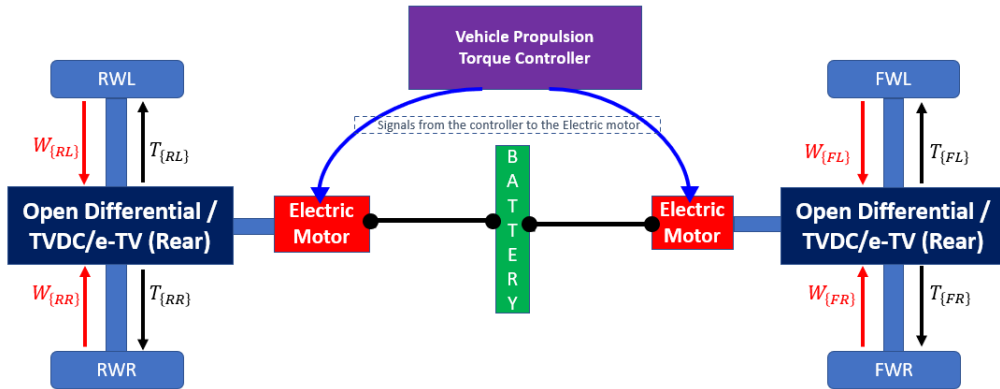


Figure 3: Schematic of AWD configuration

Modelling of 4 AWD e-axle configurations with Open Differentials at front axles and TVDC/eTV at rear axles was carried out with integration of FMUs, adapted simulink system blocks, and relevant controllers naming:

1. Open Differential(Front) and **TVDC** (Rear)- with torque distribution 50-50 logic
2. Open Differential (Front) and **TVDC** (Rear)- with Optimal torque distribution logic
3. Open Differential (Front) and **eTV** (Rear)- with torque distribution 50-50 logic
4. Open Differential (Front) and **eTV** (Rear)- with Optimal torque distribution logic

Additionally 2 RWD e-axle configurations with Open Differentials and TVDC were also modelled for comparison.

Performance and functionality analysis of eTV, TVDC and Open Differential was validated primarily and tuned while integrating AWD. Sanity check was carried out simulating AWD

configurations for CarMaker interface compatibility and physics functionality accessing system and subsystem individually to make them post processing ready. The post-processing results analyse the robustness emphasizing the changes in AWD models, which are tuned in the models enhancing the validation. Modelling subsystems and validation tests are a cycle until the best working AWD models are obtained.

Several test environments were created in CarMaker for carrying out the sanity checks and testing the completed models on various vehicle dynamics and energy efficiency performance aspects.

### 3.1 CarMaker Model Setup

Tool version used: Carmaker 10.0, Dymola v2022 and Matlab 2020b.

- Firstly, a new project folder was created on a preferred disk location, enabling CarMaker for Simulink Extras [9].
- Matlab file `cmenv.m` file was ran to link Simulink and CarMaker.
- Matlab file `eMotorLossMap.mat` , `eTVInit.m` (initialises parameters of eTV motor) was ran next.
- Simulink files of different AWD/RWD configurations were then opened, naming:
  1. `ModularAWD_OpenDiff_Volvo_TVDC_Trq_dist_logic`
  2. `ModularAWD_OpenDiff_Volvo_TVDC_Trq_50_50`
  3. `ModularAWD_OpenDiff_BW_ETV_Trq_Trq_logic`
  4. `ModularAWD_OpenDiff_BW_ETV_Trq_50_50`
  5. `ModularRWD_OpenDiff`
  6. `ModularRWD_TVDC`

CarMaker GUI setup [9] .

- Specific car model from the menu bar on CarMaker GUI was selected.
- Parameterization for the test run scenario is carried out for different modules:
  1. Vehicle: Defining vehicle data set Note: Additional parameters are discussed in A.1.
  2. Road: Parameterisation of test track/Import test tracks
  3. Maneuver: Defining drivers task while on the road , where speed and time is defined

An environment variable to the path of the license file was added (may not be required in some cases). [10]

### 3.2 CarMaker Open-XWD interface

OpenXWD configuration with Standalone vehicle model was chosen as it was possible for the user to completely parameterize the driveline with drive sources within powertrain model and the powertrain control unit can be controlled by CarMaker's control or user-defined. For modelling, complete user-defined controls of the powertrain were used. The control logics were designed in Simulink and implemented as function blocks into the powertrain models as will be described



elaborately later. When using OpenXWD-Standalone and choosing user-designed controls, several additional parameters need to be added under CarMaker vehicle settings *Additional* tab to actually let the software know about the models that are being used and create a link between interfaces and software.

Understanding CarMaker powertrain model: OpenXWD- Standalone interface was one of the critical tasks, as it is defined with two interface structures for information exchange between the powertrain model OpenXWD and the Virtual Vehicle Environment (VVE). This is the key step which determines how the modelling of modular architectures would be done as the modelling and design of subsystems will be based on the inputs/outputs. Wheel Torques  $T_{FL}$ ,  $T_{FR}$ ,  $T_{RL}$ ,  $T_{RR}$  are output variables from CarMaker VVE to the wheels. Wheels speeds  $\omega_{FL}$ ,  $\omega_{FR}$ ,  $\omega_{RL}$ ,  $\omega_{RR}$  are input variable returned from the wheels to CarMaker VVE with OpenXWD powertrain model. The simplified outline of information exchange between VVE, OpenXWD PT model and CarMaker is shown in figure 4.

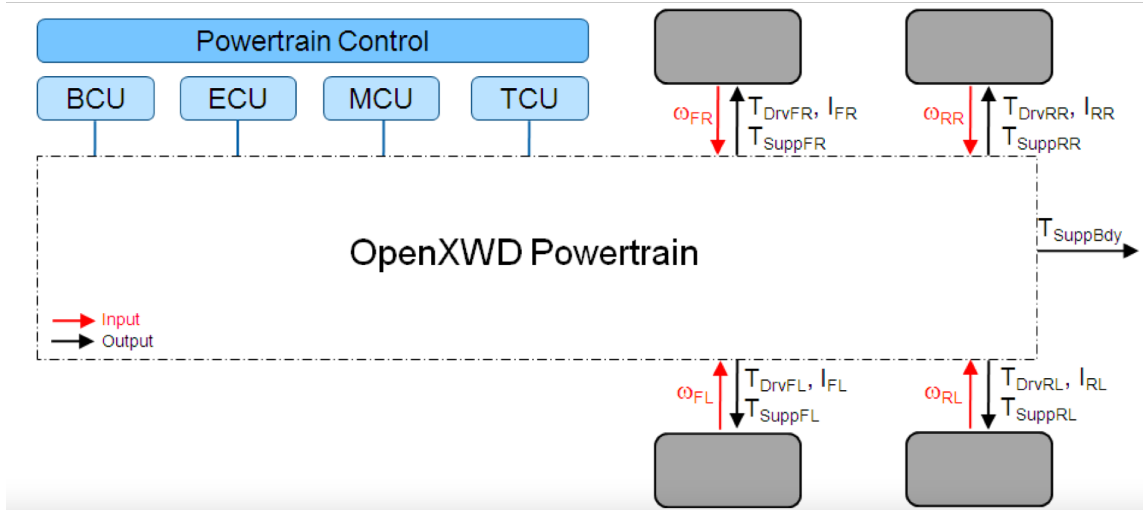


Figure 4: CarMaker OpenXWD-Standalone powertrain model interface.

Driver physical connection is defined by the driver model in CarMaker GUI which controls the vehicle lateral inputs (steering wheel inputs), longitudinal inputs (gas pedal and brake inputs). Driver torque request signal is fed to the front and rear axle propulsion systems physically connected with CarMaker model, controlling the longitudinal and lateral dynamics. Test environment and maneuver setup is done in CarMaker GUI [9] The schematic top level view of simulation model is shown in figure 5.

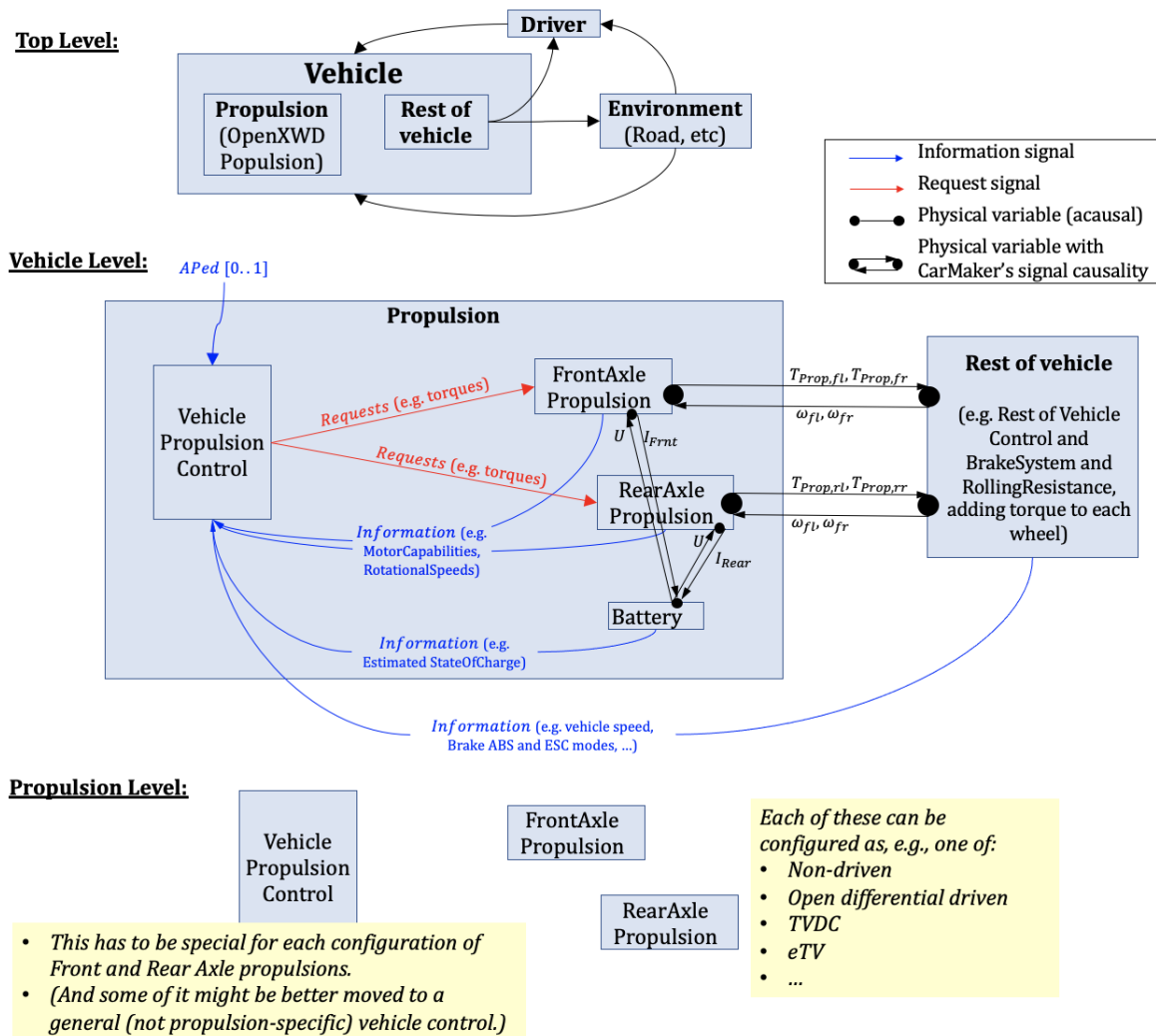


Figure 5: Simulation model top view

### 3.3 Subsystem Modelling

Subsystems can be described as the main component blocks that are interchangeable between models to make various configurations of powertrains. These models include axles with different types of torque differentials (Open diff, TVDC, and eTV), propulsion motor, and a front to rear axle torque distributor. All of these subsystems are modular and therefore were combined in different manner to create different AWD and RWD powertrains.

### 3.3.1 Open Differential axle

Modelica equation-based approach was implemented to build the driveline using equations. The physical relationship among the components within the open-diff axle were defined by a series of equations. The equations require a set of inputs for calculating a certain set of unknowns which are then outputted. This script was then saved and converted into a functional mock-up interface (FMI) using the Model Exchange format [3] which can then be imported into modelling tools as a functional mock-up unit (FMU) as seen in figure 6 below. The open-diff FMU uses

the maximum motor torque, and the left and right wheel angular speeds to compute the left and right wheel torques, and the motor speed which are the outputs from this FMU.

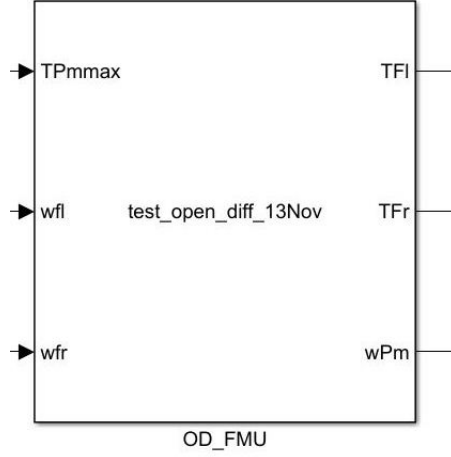


Figure 6: Open differential FMU (Co-Simulation)

The open differential e-axes were assumed to have a single speed gear of ratio 10 and was included inside this physical modelling of the open-diff. The torque and angular speeds relationship can be given by the following equations:

$$T_{InGear} = T_{OutGear} / Ratio \quad (2)$$

$$w_{InGear} = w_{OutGear} \cdot Ratio \quad (3)$$

A simple angular speeds and 50-50 torque distribution left to right (working principal of the open-diff) can be represented by the following equations:

$$T_{OutGear} = T_{fl} + T_{fr} \quad (4)$$

$$w_{OutGear} = (w_{dfl} + w_{dfr}) / 2 \quad (5)$$

Each wheel shaft were considered to have a torsional stiffness of 11459 Nm/rad [3] which were also included into the FMU for simplicity in later stages of modelling.

$$der(T_{fr}) = c_{EachDriveShaft} \cdot (w_{dfr} - w_{fr}) \quad (6)$$

$$der(T_{fl}) = c_{EachDriveShaft} \cdot (w_{dfl} - w_{fl}) \quad (7)$$

An assumption on Inertia relationship of the system were given by the following equation:

$$J_{InShaft} \cdot der(w_{Pm}) = T_{PmMax} - (T_{InGear}); \quad (8)$$

The above relationships were based on the physical model shown in figure 7 below. The picture gives a more clear understanding of the level of detail that was added into the model. It also shows where a particular physical component was considered during modelling.

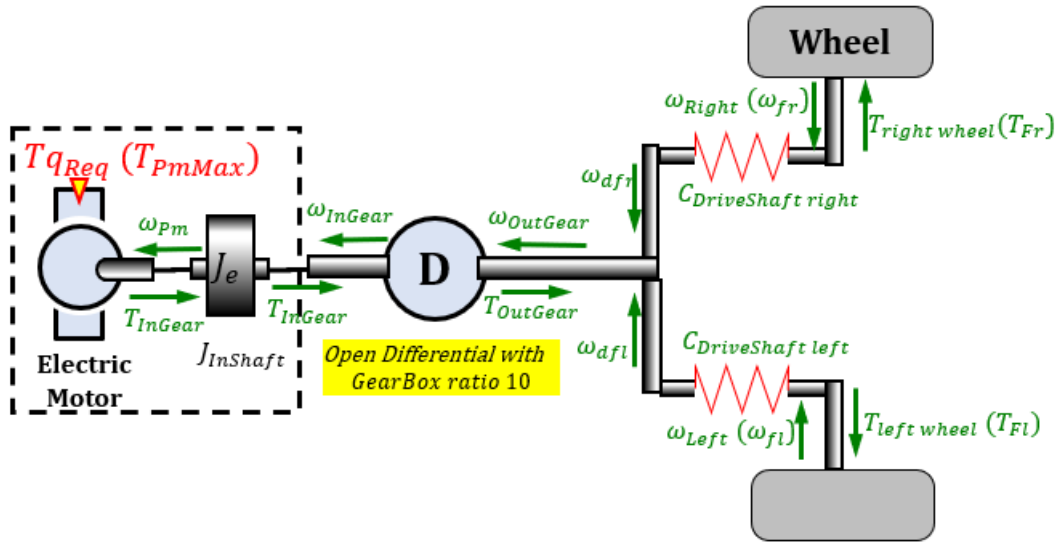


Figure 7: Open Differential Physical Model

The next stage of modelling the open-diff e-axle involves importing the Open-diff FMU into Simulink (main modelling tool). The input variables can be edited by double clicking the Open-diff FMU. Based on CarMaker inputs and outputs for OpenXWD-Standalone, wheel speeds from CarMaker dictionary (Orange blocks) are fed as inputs and the output wheel torques are saved in CarMaker torque dictionaries [9]. A power consumption model is also embedded into the axle models to calculate power consumption on an axle level. This was done to support modularity which would mean no editing of the power consumption model is required if for example this axle is used for either an FWD, RWD or AWD configuration, only the power consumption need to be added on a full powertrain model level based on the number of axles used. The open-diff e-axle model in Simulink is given in figure 8.

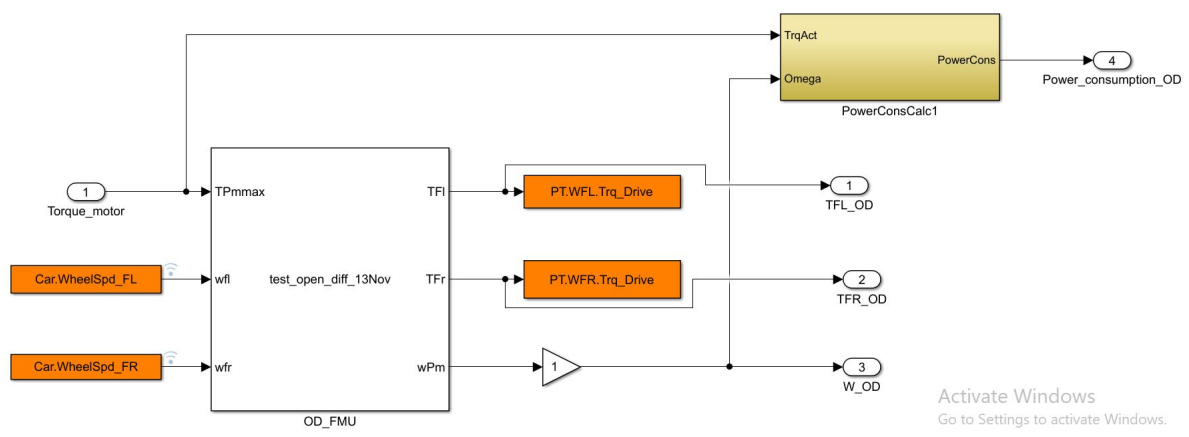


Figure 8: Open differential e-Axle simulink block diagram

The power consumption model provided by BW was modified to be compatible with modularity approach of the full models. As seen in figure 9 the function block uses the torque and speed

output of the motor and apply a power loss efficiency factor based on a power loss map of the BW motor model to compute the power consumption. A script was made to calculate the total energy consumption during a full simulation as described later in simulation part.

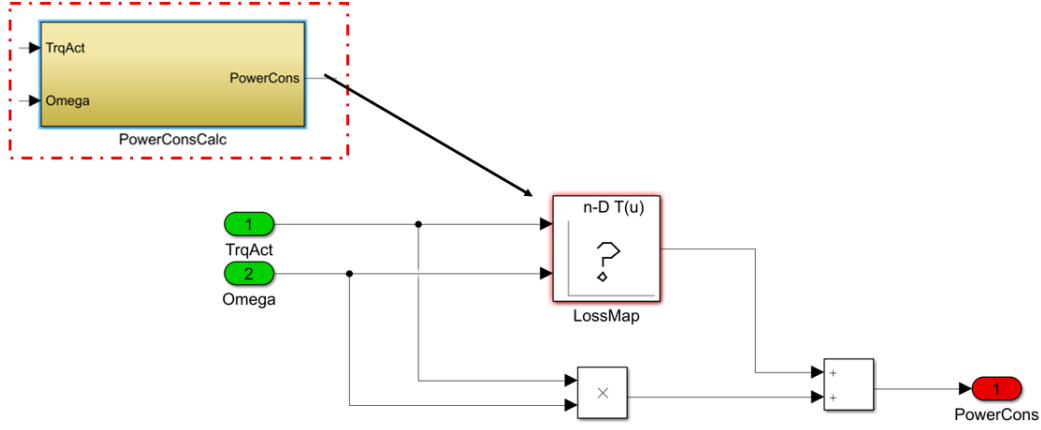


Figure 9: Power consumption block diagram

### 3.3.2 Volvo TVDC axle

The TVDC model is also based on equation-based Modelica FMI imported onto simulink. The control logic for the TVDC was from Chirag's thesis [3]. TVDC model is defined using discrete state variables -1, 0, or +1 representing negative slip, no slip, or positive slip. The physical relationship between the components can be defined by the following equations:

$$T_{InGear} = T_{OutGear} / Ratio \quad (9)$$

$$w_{InGear} = w_{OutGear} \cdot Ratio \quad (10)$$

Dual clutches on both shafts are responsible for the torque vectoring on a simple open-diff model. A simple 50-50 torque distribution left to right (working principal of the open-diff) and the angular speeds can be represented by the following equations:

$$T_{OutGear} = T_{rl} + T_{rr} \quad (11)$$

$$w_{OutGear} = (w_{drl} + w_{drr}) / 2 \quad (12)$$

Each wheel shaft were considered to have a torsional stiffness of 11459 Nm/rad [refer to chirag's report for the reason of choosing this value] which were also included into the FMU for simplicity in later stages of modelling.

$$der(T_{rr}) = c_{(EachDriveShaft)} \cdot (w_{(afterclutchrr)} - w_{rr}) \quad (13)$$

$$der(T_{rl}) = c_{(EachDriveShaft)} \cdot (w_{(aftercluthrl)} - w_{rl}) \quad (14)$$

An assumption on Inertia relationship of the system were given by the following equation:

$$J_{InShaft} \cdot der(w_{Pm}) = T_{PmMax} - (T_{InGear}); \quad (15)$$

The above relationships were based on the physical model shown in figure 10 below. The picture gives a more clear understanding of the level of detail that was added into the model. It also shows where a particular physical component was considered during modelling.

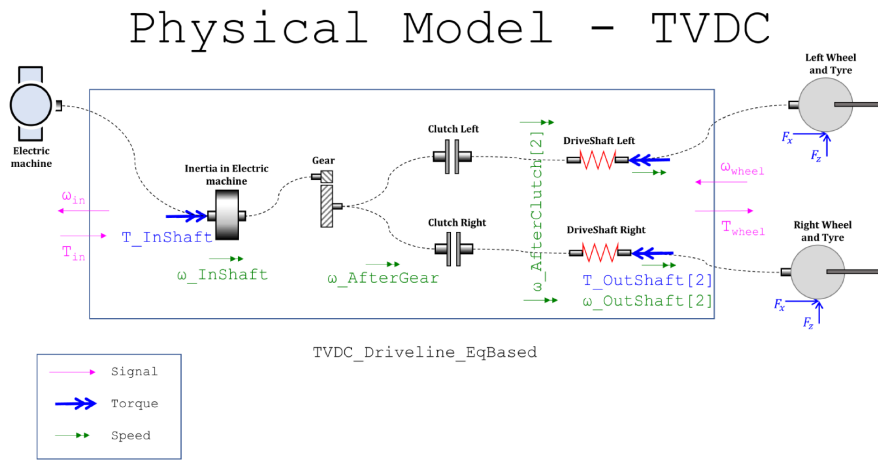


Figure 10: TVDC Physical Modelling ([3])

In addition to the equations used in the open-diff model, the following (general) clutch actuation logic is also incorporated into the TVDC FMU [3]:

```

if abs(Slip) == 1 then
    der ( T_OutShaft ) = sign(Slip)* der ( T_ClutchCap ) ;
//Using T_OutShaft = sign(Slip)*T_ClutchCap ;
else
    w_InShaft /Ratio = w_AfterClutch ;
end if ;
w_Rel = w_InShaft /Ratio - w_AfterClutch ;
when pre (Slip) == 0 and T_OutShaft > T_ClutchCap then
    Slip = +1;
    reinit (T_OutShaft , +T_ClutchCap ) ;
elsewhen pre (Slip) == 0 and T_OutShaft < T_ClutchCap then
    Slip = 1;
    reinit (T_OutShaft , T_ClutchCap ) ;
elsewhen pre (Slip) == +1 and w_Rel < 0 then
    Slip = 0 ;
elsewhen pre (Slip) == 1 and w_Rel > 0 then
    Slip = 0 ;
end when ;

```

A control logic function block for the actuation control of clutch provides the signal  $T_{ClutchCapReq}$  and the maximum torque capacity of the clutches is defined by the  $T_{ClutchCap}$ . The control logic function block for the TVDC can be replaced with a more complex controller for better performance of the TVDC e-axle. The controller uses an algorithm where the steering wheel angle and normal loads acting on the wheel as in figure 10. The control logic (shown below) is based on torque vectoring and propulsion to introduce the torque vectoring function in the driveline. During cornering, the outer wheel experiences a load transfer due to the centrifugal

force and the later acceleration of the vehicle. To overcome this, a higher propulsive force is supplied to this wheel. Hence, more torque is given to the outer wheels. The torque delivered to each wheel depends on the normal load acting wheel as this is the deciding factor for transfer of load [3].

```
function [TqCapLeft,TqCapRight] = fcn(Trq_in,delta,FzRL,FzRR)
    FzR= FzRL+FzRR;
    if Trq_in>0
        Trq=Trq_in;
    else
        Trq=0;
    end
    if delta>0.05
        TqCapLeft=FzRL/FzR*Trq;
        TqCapRight=1300;
    elseif delta<-0.05
        TqCapLeft=1300;
        TqCapRight=FzRR/FzR*Trq;
    else
        TqCapLeft=1300; TqCapRight=1300;
    end
end
```

Similar to the open differential axle discussed previously, the only difference between these two axles is the differential FMU block. All other inputs/outputs follow the same format and therefore are connected in a similar manner. The Simulink model of the TVDC e-axle is given in figure 11 below along with the control logic function block.

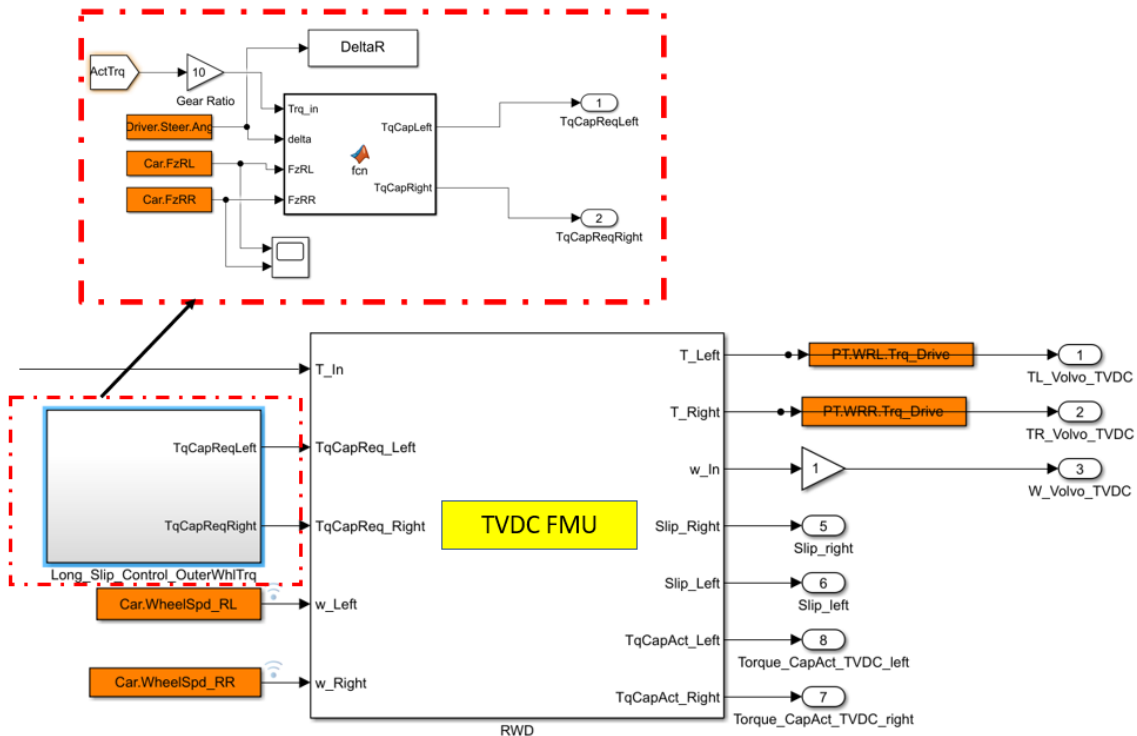


Figure 11: TVDC e-Axle simulink block diagram

### 3.3.3 BorgWarner eTV axle

The core working principal of eTV motor (*eTVMot*) was modelled by BW. The model was altered to adapt with the car maker environment. A simple controller function block for the eTV was designed in Simulink which differentiates the left and right wheel torques based on the steering angle input dictionary of CarMaker. The simple controller uses the steering angle and applies a gain to request a differential torque signal which is then fed into the eTV motor model, see figure 12. This controller function block can be replaced with a more complex controller of the eTV for better performance of the model. The eTV axle model also contains an additional open-diff function block to calculate the motor speed as this is required as an input to the CarMaker.

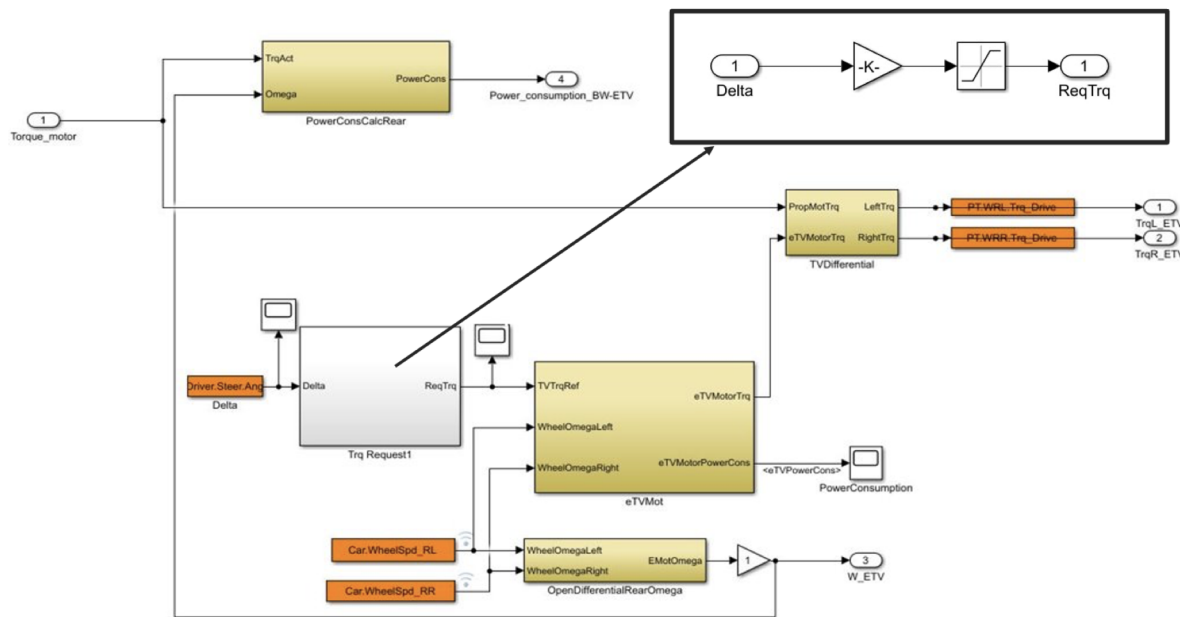


Figure 12: eTV Axle Block Diagram with the simple eTV controller

The eTV motor model uses this signal combined with left and right wheel speeds to compute the eTV motor speed and torque. A delay and a saturation function block added to the eTV torque makes the modelling more realistic. A delay is required for the feedback loop of the motor speed. A power consumption function block for the eTV motor is also added with a constant efficiency (instead of an efficiency map like the propulsion motor model) for simplicity. The computed eTV motor torque signal is used by the *TVDifferential* function block to distribute a negative torque to the inner wheel and a positive torque to the outer wheel during a turn.

Figure 13 below shows the detailed eTV motor simulink block diagram with each of the "golden" function blocks. It consists of a *GearBox*, *EMotDyn*, *EMotTrqSaturation*, and *eTVPowerConsumption* block diagrams. *GearBox* provides the gear ratio of the eTV motor, *EMotDyn* and *EMotTrqSaturation* adds more accuracy to the eTV motor modelling by adding physical properties of the motor into the model, and *eTVPowerConsumption* calculates the power usage of the eTV motor which can be added to the total power or energy consumption of the vehicle for example.



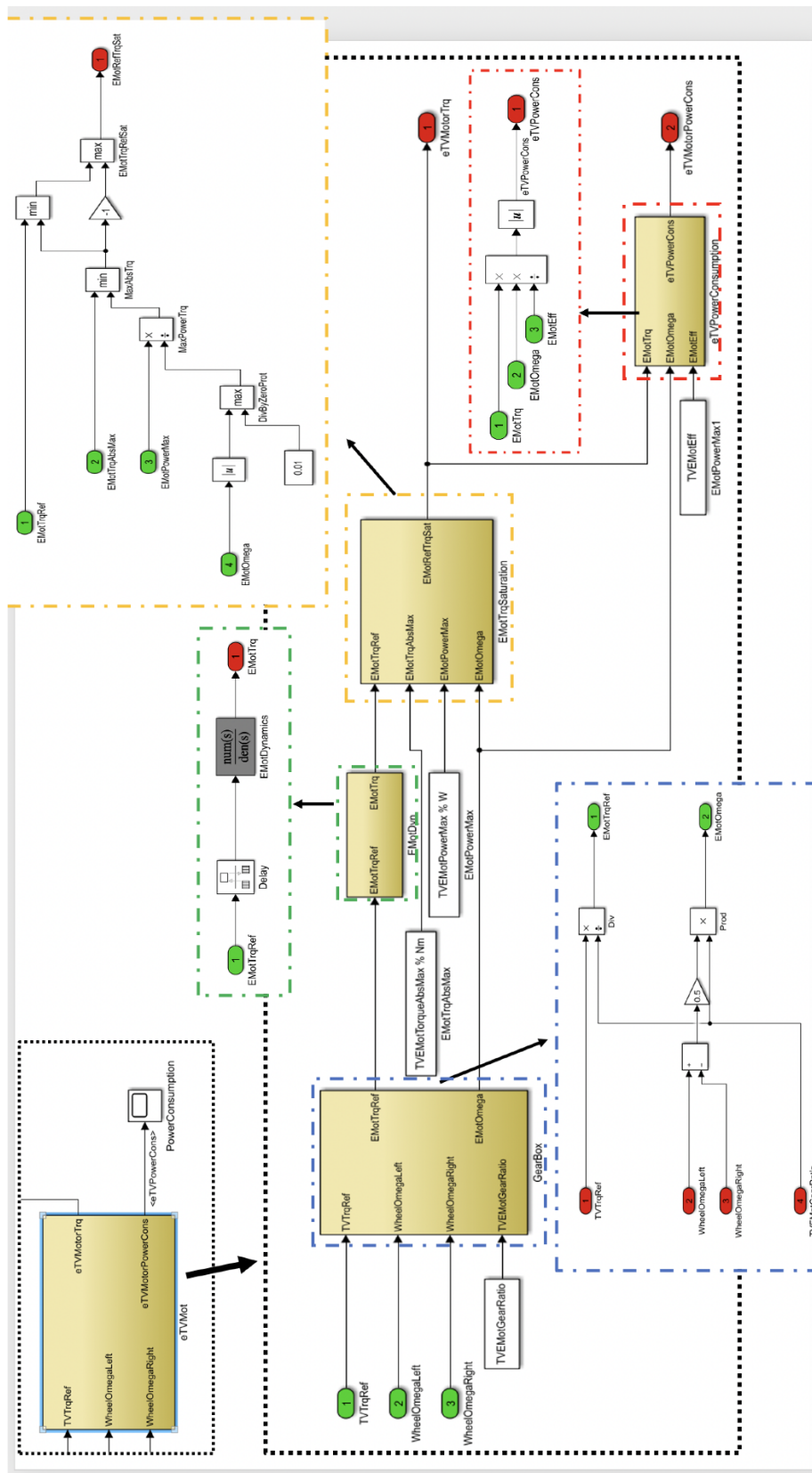


Figure 13: Detailed eTV motor (eTVMot) Block Diagram

### 3.3.4 Propulsion motor model

Simple 200 kW propulsion motor model provided by BW was used as prime motors. As seen in figure 14 below, the model does not include any motor inertia because the inertia was modelled inside the axle models as total inertia of the system. The model uses motor power and speed to match and compare the requested torque (*SaturationDynamic*) from the motor and outputs the actual torque produced by the motor. This motor has negative working regions which was not used and included within the scope of this project. The model also has editable power and torque limits and can be replaced by a more complex motor model.

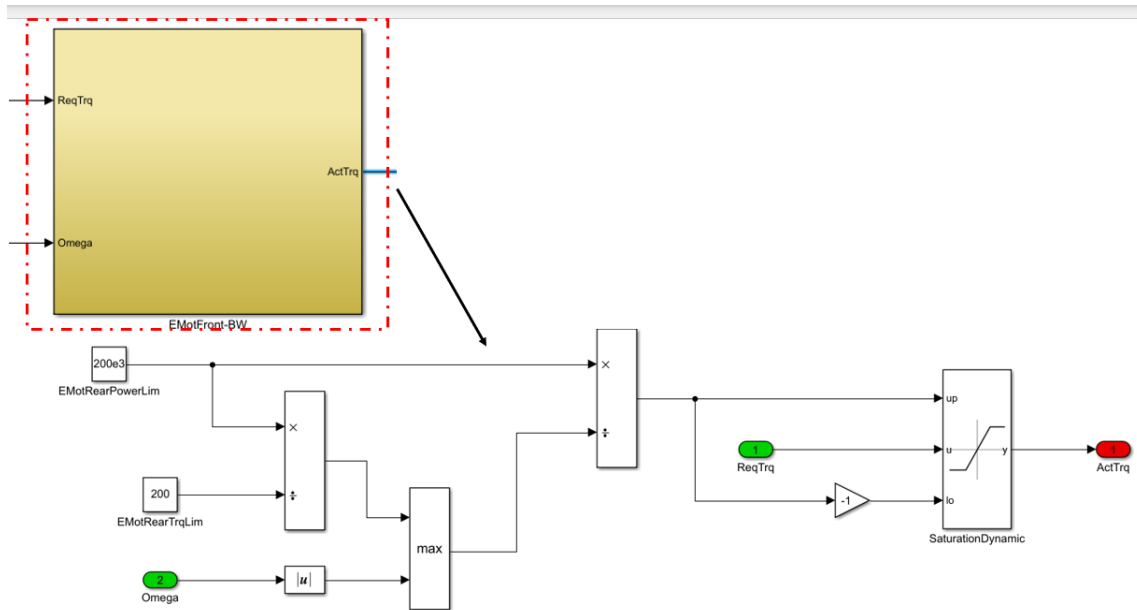


Figure 14: Propulsion Motor Block Diagram

### 3.3.5 Front to Rear axle torque distributors

Torque distributor logics were also designed for requesting torques from the front and rear motors in case of AWD configurations. The torque distributors simply use the maximum power of the motor and apply a fraction based on the gas pedal position (0 to 1). This power request is divided by the motor speed to send the torque request signal to the motors. The 50-50 torque distributor sends the same request to both front and rear motor but each motor then outputs half of the total torque request. The Optimal torque distributor function block, as seen in figure 15, has an additional logic for distributing the torque requests to the front and rear motors. It uses the vertical forces on the axles and divides the torque requests accordingly. Higher torque is sent to the axle which has higher vertical load. The models has saturation blocks to keep the torque signals with limits of the motors and a very small constant is added to the input motor speed signal to avoid infinity errors in Simulink. This function block can be replaced with a more complex controller such as one with rear axle/motor disconnect function for better energy efficiencies.

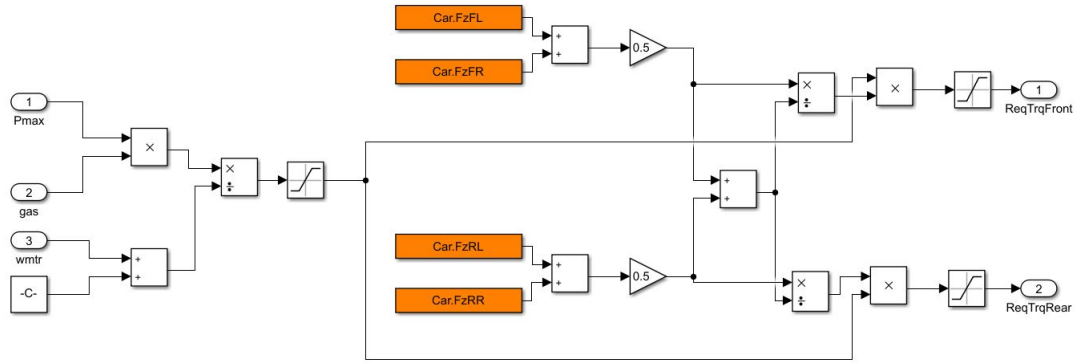


Figure 15: Optimum front to rear axle torque distributor controller

### 3.4 Vehicle (Configurations) Modelling

Volvo XC90, figure 16, was used as a vehicle model. The CM built-in steering, suspension, tire, and brake models for the car were used.



Figure 16: Car Model used for the Project

For the vehicle powertrain model, OpenXWD-Standalone was used as it allows the use of any user designed powertrain model for the vehicle i.e. the powertrain is empty inside the software and to be filled by a user designed complete powertrain which was done in simulink in this case. It should be noted that all CarMaker software built-in longitudinal and lateral control for the vehicle model was turned off. This was done to solely measure the performances of the differentials without any other variables in the comparison. A set of additional parameters are required to be set in CarMaker under vehicle settings to ensure the proper communication between CarMaker and user designed powertrain. When using OpenXWD-Standalone interface, the state of the driven wheels, gearbox, other PT controllers need to be updated in CarMaker even though these are defined in user designed powertrain model [9]. A.1 shows the set of additional parameters used.

All modelled axles were designed to use the same inputs and outputs based on OpenXWD-Standalone interfaces. This allowed for designing simple modular axles which were assigned into a separate function block so that the axle models can be swapped with each other and different driveline configurations can be achieved.

The axles, control logics and propulsion motors can be combined in many ways to form a full

powertrain. Many combinations are possible but within the scope of this project, the following powertrain configurations were modelled by interchanging the subsystems:

### 3.4.1 AWD: Open Differential (Front) & TVDC(Rear) with 50-50 torque distribution

The full powertrain model in figure 17 consists of a open-differential front axle on top and a TVDC rear axle. A dual motor setup with identical motors sitting on each axle was opted. The 50-50 torque distributor uses *GasPedal* position signal from CarMaker driver model dictionary and calculates the requested torque signals which are sent to both motors. Then half of the actual motor torque is sent to the differential. Since motor speed is an input to CarMaker and there are two motors, an average of the two is sent to CarMaker. Each function block can be switched with other more detailed versions and also can be replaced entirely.

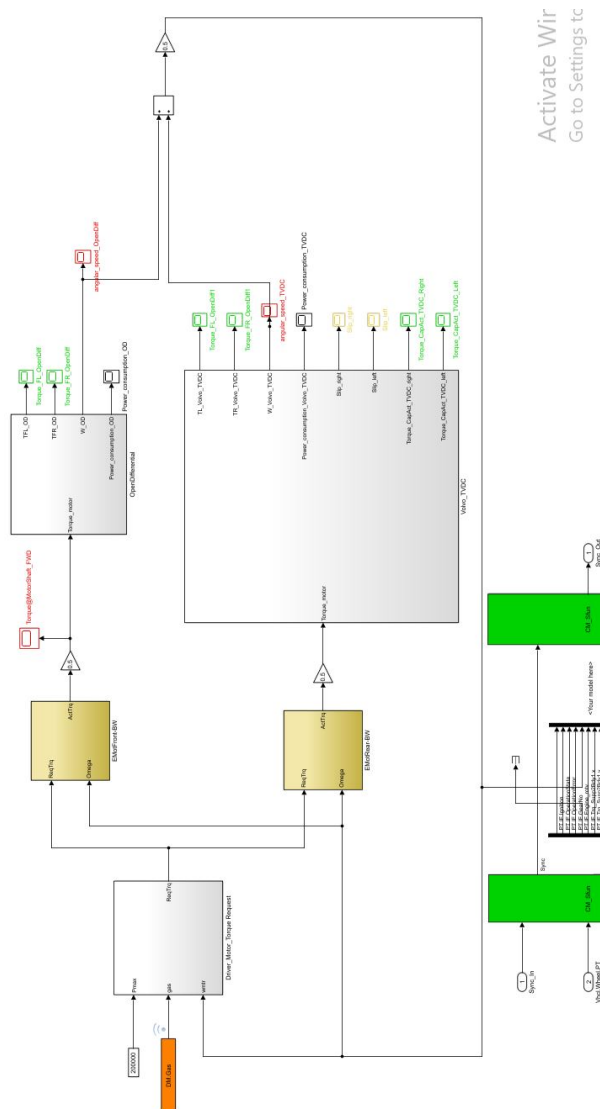


Figure 17: Modular AWD-Open Differential(front) and TVDC(rear) Simulink Block with 50-50 Torque Distribution Control Logic

### 3.4.2 AWD: Open Differential (Front) & TVDC (Rear) with optimal torque distribution

The only difference between the previous and this configuration of AWD powertrain is the control logic for the torque request distribution for front and rear motors. It has been replaced with the optimal torque request distributor as seen in figure 18 below.

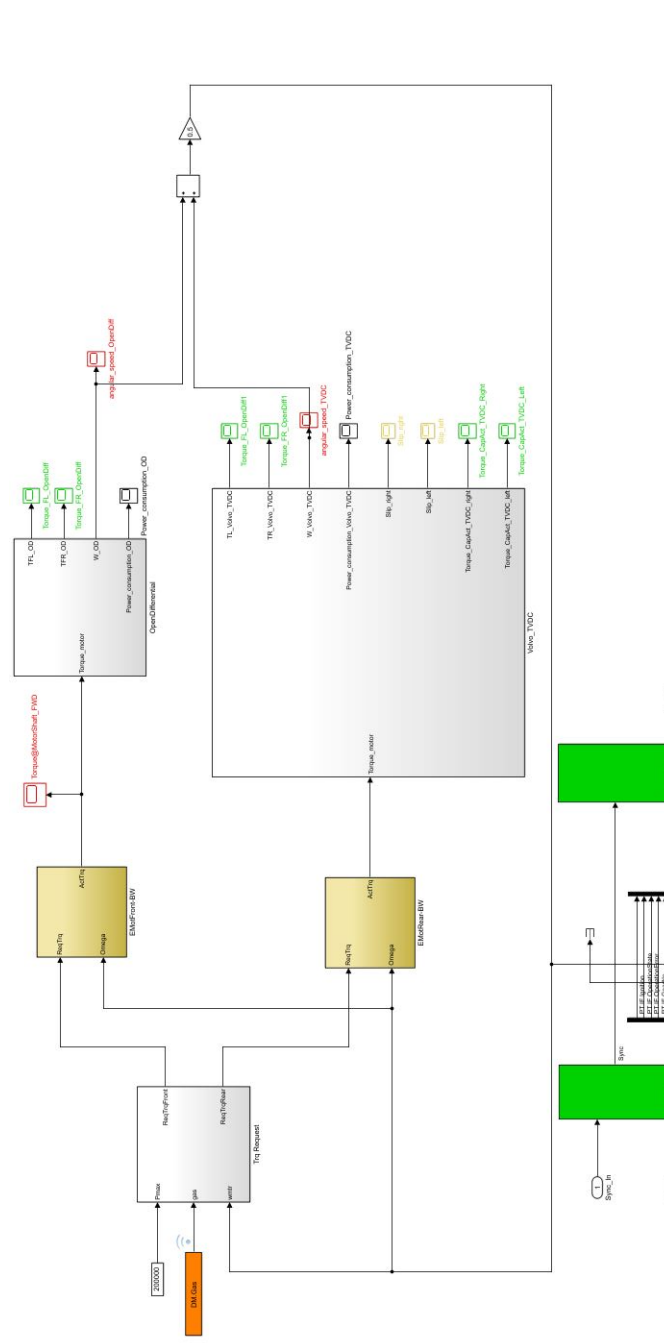
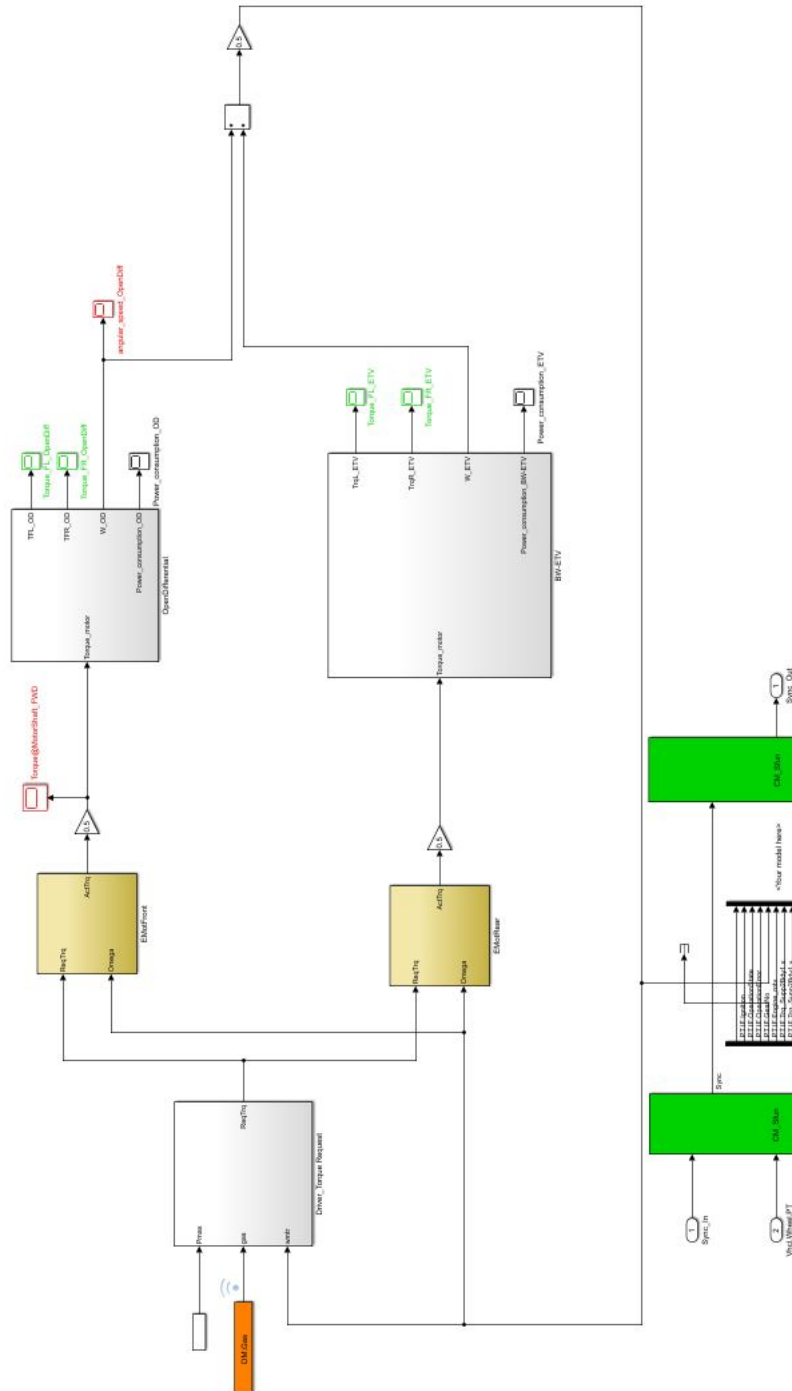


Figure 18: Modular AWD-Open Differential(front) and TVDC(rear) Simulink Block with Optimal Torque Distribution Control Logic



### 3.4.4 AWD: Open Differential (Front) & e-TV (Rear) with optimal torque distribution

The only difference between the previous and this configuration of AWD powertrain is the control logic for the torque request distribution for front and rear motors. It has been replaced with the optimal torque request distributor as seen in figure 20 below.

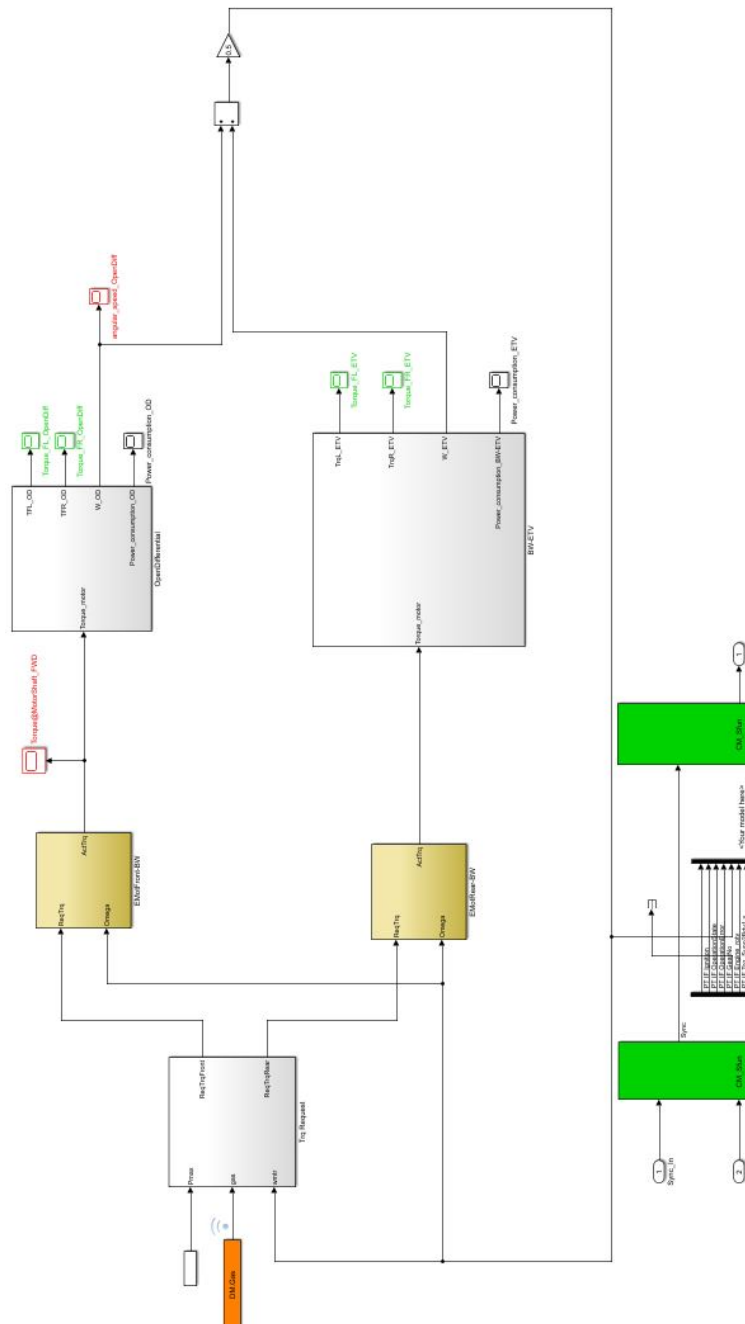
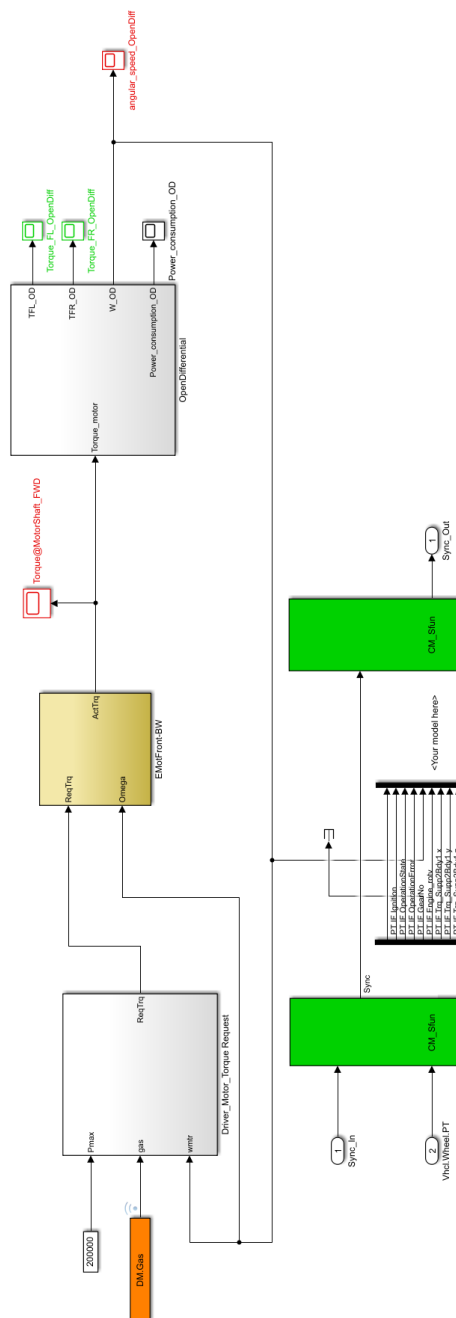


Figure 20: Modular AWD-Open Differential(front) and eTV(rear) Simulink Block with Optimal Torque Distribution Control Logic





### 3.4.6 RWD: TVDC on the Rear axle

The only difference between the previous and this configuration of RWD powertrain is the rear axle where open differential has been replaced by TVDC as seen in figure 22 below.

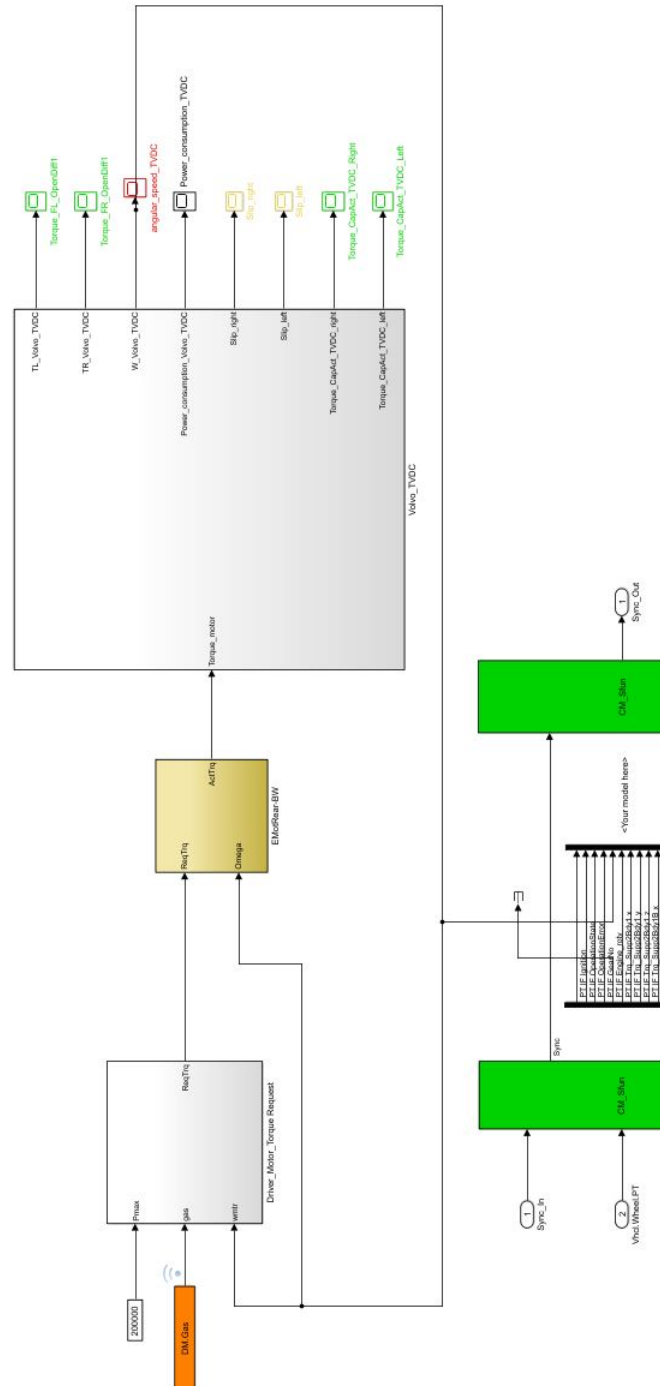


Figure 22: Modular RWD- TVDC Simulink Block

## 4 Simulation

Simulation includes building a virtual environment for the validation and then the validation and verification itself.

First, simple tracks were created in the program Car-maker, and some vehicles were simulated on these tracks to get accustomed to the program. Then, the subsystems configurations provided by the modelling team were imported to Car-maker to simulate them in specific environments. These environments consisted of test tracks that were created to analyze the dynamics and the energy consumption of the configurations. The analysis was done by studying parameters like friction, average speed, maximum entry speed, energy consumption, and the duration time as well as the variables explained in section 2.4.

Average speed of the vehicle simply means the mean speed of the vehicle over the whole course. The maximum entry speed is the highest speed a vehicle can achieve before a corner i.e., just before any drastic increase in lateral forces on the wheels are observed.

### 4.1 Vehicle dynamics

Within the scope of the project, vehicle dynamics was an essential to be studied in order to assess the performance of the configurations with the different torque vectoring systems and establish a comparison between them. To perform this analysis, two test tracks were created in the CM environment: The downhill track and the slalom track.

#### 4.1.1 Downhill track

The track, shown in 23, begins with a straight segment of 600 meters, with a slope of 5 grade or 2.86 degrees. It is followed by a curve of 90 degrees with a 50m radius, followed by a straight segment of 60m with a slope of 0 degree. This track tests the different vehicle configurations' performance in a downhill combined with a sharp corner.

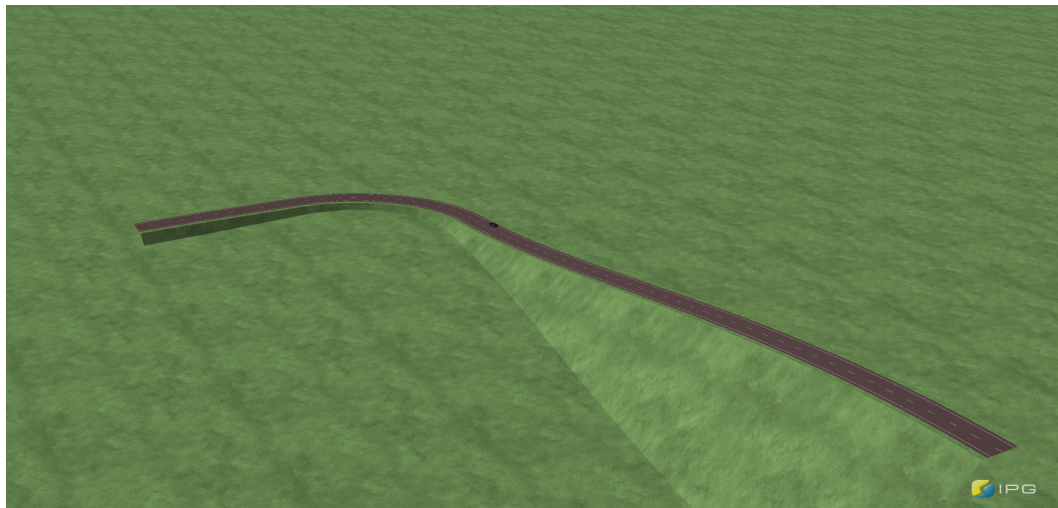


Figure 23: Downhill track

#### 4.1.1.1 Maximum entry speed test

Different simulations were conducted on this track, of which the first was the maximum entry speed test. This test was about determining the maximum speed that the vehicle at which the vehicle would complete the course without running off-track. The main purpose of this test was to analyze how the behaviour of the torque vectoring system during the corner navigation, when being pushed to the limit. This was done by steadily increasing the intended speed of the vehicle by increments of 1 km/h till it reached a speed where it ran off-course and a simulation error was obtained. The speed was then determined at the state where the vehicle was just about to enter the corner, in other words, just before any lateral forces would arise. The friction coefficient  $\mu$  was set to a value of 1 in order to obtain an optimal grip thus, ignore the effect of it on the torque vectoring system. Additionally, by choosing the "speed control" mode in Car-maker, no braking force was applied. This was all done to isolate the effect of speed.

#### 4.1.1.2 Friction test

The second test done was the friction test. The focus of this test was to determine the lowest friction at which the vehicle could complete the course without running off-course. This was done by lowering the friction coefficient value by increments of 0.01 until the vehicle would ran off-course and a simulation error was obtained. The speed was set at a fixed value of 60 km/h, so that the friction values implemented could be at around 0.4, which simulates the case of a wet road. Similar to the maximum entry speed test, "speed control" mode was chosen to eliminate any braking effect.

#### 4.1.1.3 Variables comparison test

The third and last test done on this track was the variables-comparison test. The focus of this test was to analyse and study the different variables explained in section 2.4. It was done for only two models, the AWD eTV model and the AWD TVDC model at a speed of 84 km/h, which corresponds to the speed of the worse performing model between these two in the maximum entry speed test. The simulation data was then exported and post-processed in Matlab in order to obtain plots of the variables and compare them for the two models. The variables were plotted with respect to distance, which is the measured length of the track. The reason as to why this plot analysis was done for only the AWD models was to make the comparison fair. Including the RWD TVDC model wouldn't allow a reasonable assessment of the torque vectoring systems as it has a different drive configuration and this would affect the results. Concerning the choice of the track for this analysis, it was done because the downhill track was specifically requested by the stakeholders to perform the simulations on. Moreover, since it only has one sharp curve, the analysis would be easier to do and the plots would be clearer to explain and for the reader to understand.

### 4.1.2 Slalom track

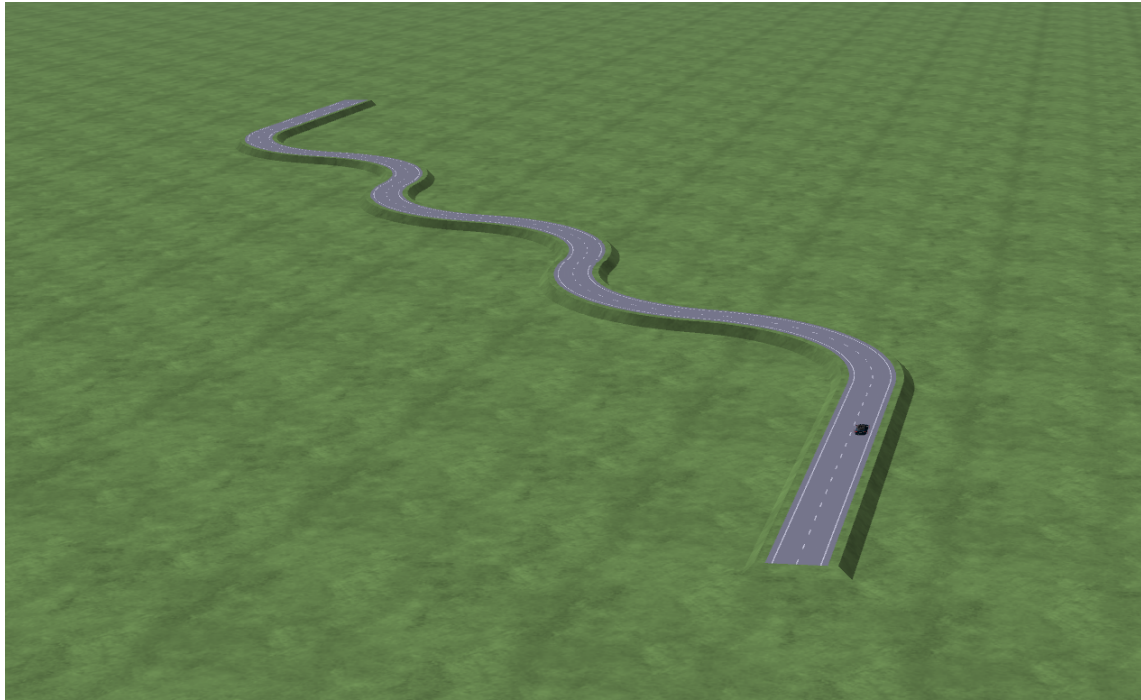


Figure 24: Slalom track

The slalom track that is shown in 24 consists of a straight segment of 400 meters, then a series of 6 left and right turns, each and everyone of the turn has an angle of 80 degrees and a radius of 50 m, and then after it it's straight for 60 m. All the segments are set to 0 degree slope.

#### 4.1.2.1 Maximum average speed test

The first test done on this track was the maximum average speed test. Done in a similar way as the maximum entry speed test, the goal was to find the maximum speed at which the vehicle could complete the course and then determining the average speed for the whole course from the log data. The time duration was also logged to compare the performance and agility of the models.

#### 4.1.2.2 Friction test

The second test done was the friction test done in a exactly similar way to the one described in the downhill track, but a fixed speed of 50 km/h.

#### 4.1.2.3 Variables comparison test

The third and last test was the variables-comparison test done at 76 km/h for the AWD TVDC and AWD eTV models. It was done as a way to verify the behaviour seen in the variables-comparison test done on the downhill track. Thus, the focus was to plot the variables that are related to lateral dynamics, since this test consists mainly of alternating curves.

## 4.2 Energy Consumption

Another important aspect in the project was the energy efficiency of the models. Only one test made here, which was the energy consumption. It was calculated by performing simulations on a handling test track provided by Volvo.

### 4.2.1 Hällered handling track

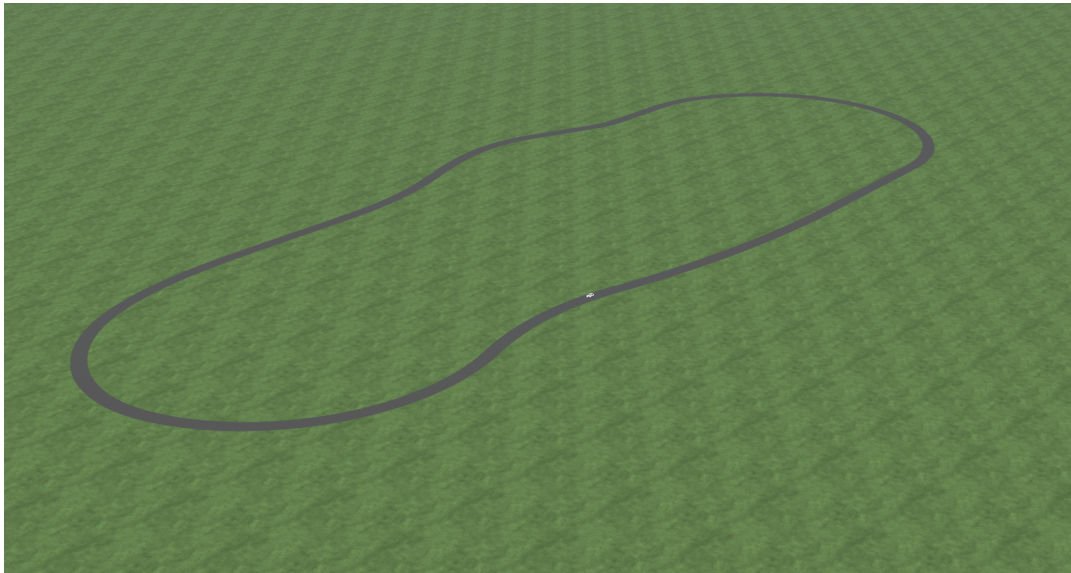


Figure 25: Hällered's handling track 2

The Hällered track, shown in 25 is 1.7 km long and is used to test the handling of the cars by Volvo. The reason as to why this track was used to determine the energy consumption of the configurations was due to lack of time. In other words, time wasn't sufficient to create an environment with a track that would mimic real world city driving for example. However, it was deemed to be reasonable to use this track as long as the parameters were the same for all simulations and the speed mode chosen was appropriate. What is meant by the latter is that in this case, "speed control" mode wasn't chosen as it wouldn't simulate real world driving. "IPG driver mode" was chosen instead, and it incorporates an artificial driver controlled by the software's algorithm. To clarify, the driver will try to get up to the intended speed set by the user, but only if the track allows to. In other words, the driver will apply braking as necessary, for example, if the speed is deemed to be too high when approaching a curve.

#### 4.2.1.1 Energy test

The simulation was done by setting the intended speed to 120 km/h and driving a bit less than 4 laps on the track to simulate extended driving. On a side note, even though the speed was set to 120 km/h, the measured average speed was around 80 km/h for all models, due to the fact that the "IPG driver mode" that was selected. The energy consumption was then captured in Simulink by integrating the power consumption of the models and then integrating the energy consumption in Matlab to get the total energy consumption in KJ/m.

An important thing to clarify is that apart from the variables-comparison test, all tests mentioned previously in the downhill track, slalom track and Hällered track were done for all models

provided by the modelling team. The focus in these tests was though on the AWD TVDC model, AWD eTV model and RWD TVDC model. The AWD eTV model with control logic was used to see how the control logic would affect the results compared to the model without one. In the same way, the RWD open-diff model was used to see how the absence of a torque vectoring system would influence the performance.

## 5 Results and Discussion

The results for all the simulations are listed in the tables below and will be discussed, compared and interpreted in the following subsections.

### 5.1 Downhill track

The table below shows the maximum entry speed for all the different configurations on the downhill track when the friction  $\mu$  was fixed throughout the simulations and set to a fix value of 1.

Vehicle configuration	Max. entry speed (km/h) at $\mu = 1$
AWD TVDC (3.4.1)	83.88
AWD eTV (3.4.3)	84.85
AWD eTV control logic (3.4.4)	84.85
RWD TVDC (3.4.6)	82.87
RWD open diff (3.4.5)	82.87

Table 1: Maximum entry speed test performed with Volvo XC90

As it can be seen in the results above, the AWD eTV models had the highest entry speed followed by the AWD TVDC model and finally the RWD models. The fact that the eTV model was able to have the highest speed proves that the torque vectoring is superior in managing a sharp curve at a high speed, in other words when being pushed to the limit. The reason to that might be that the higher complexity of the eTV works in its favor with its ability to provide both positive and negative torque as needed. The AWD TVDC model performs slightly worse in comparison, and this might be due to the system being simpler and not being able to provide negative torque, but only positive torque. The RWD models came last which was expected since they don't have the added traction in the front. It was noticed that the model would immediately oversteer and run off-course when pushed to a speed, higher that it can handle.

It can be seen that there was no difference between the eTV model with control logic and the eTV one meaning that the logic didn't provide any benefit in this specific test. The same thing was observed between the RWD TVDC and RWD open-diff models. This was a bit unexpected as the torque vectoring system would be expected to help the car turn faster. These show however that the drive configuration used might play a bigger role in determining which car that can enter the corner the fastest. In other words, an AWD configuration might add more benefits than the torque vectoring system in this specific test.

Worth adding that the eTV model had a strange behaviour at 83 km/h. Since it could manage the course at 84.85 km/h, one would logically think that it can do it at a lower speed. However, at this intended speed, the model over-steered at the curve and then drifted out of course after the curve. Taking into consideration that no braking was used in the simulation, and with no slip-control in the model this might imply that the torque vectoring system isn't designed to handle a scenario like this. With that said, no reasonable explanation was found to fully explain this phenomena but this indicate that more testing should be done to investigate it.

The table below shows the results for the lowest friction values at which the vehicles stays on-course for all the different configurations on the downhill track. The vehicle's intended speed is

set to 60 km/h.

Vehicle configuration	Lowest manageable $\mu$ at 60 km/h
AWD TVDC (3.4.1)	0.28
AWD eTV (3.4.3)	0.25
AWD eTV with control logic (3.4.4)	0.25
RWD TVDC (3.4.6)	0.29
RWD open diff (3.4.5)	0.34

Table 2: Friction test for downhill track with Volvo XC90

The results show that once again the eTV AWD models perform better in this test and manage the track at the lowest friction, followed by the AWD TVDC, the RWD TVDC and the RWD open-diff model. A considerable difference is observed between the eTV and TVDC, showing the potential of a more advanced system. It can also be seen that when the friction comes to play the torque vectoring systems show their importance and capability. Comparing the RWD TVDC and the RWD open-diff show quite a difference, proving that torque vectoring provide much better traction and stability in slippery conditions.

## 5.2 Slalom track

The table below shows the results for the transport time and maximum average speed for all the different configurations on the slalom track when the friction  $\mu$  was set to a fix value of 1.

Vehicle configuration	Transport time (s)	Maximum average speed (km/h) at $\mu = 1$
AWD TVDC (3.4.1)	46.70	66.61
AWD eTV (3.4.3)	46.58	66.66
AWD eTV with control logic (3.4.4)	46.58	66.68
RWD TVDC (3.4.6)	46.73	66.38
RWD open diff (3.4.5)	47.05	66.15

Table 3: Maximum average speed test with Volvo XC90

Just like the downhill track, the results for the slalom track follow a similar trend; The AWD models completed the track the fastest and with the shortest transport time, with the eTV model in this track had the fastest time, implying that this model is the most agile in this type of driving.

With that being said, no big difference was found between the models, which implies that with an optimal grip, a torque vectoring system doesn't add much benefit in being able to drive that much faster. In other words, spiritual driving isn't the main focus of the system.

The table below shows the results for the lowest friction values at which the vehicles stays on-course for all the different configurations on the slalom track. The vehicle's intended speed is



set to 50 km/h.

Vehicle configuration	Lowest manageable $\mu$ at 50 km/h
AWD TVDC (3.4.1)	0.42
AWD eTV (3.4.3)	0.44
AWD eTV with control logic (3.4.4)	0.44
RWD TVDC (3.4.6)	0.42
RWD open diff (3.4.5)	0.43

Table 4: Friction test for slalom track with Volvo XC90

In this case, the results are a bit different than what is seen before. The AWD and RWD TVDC models are able to complete the course at the lowest friction, followed by the RWD open-diff and the AWD eTV models. What is most surprising is that the RWD open-diff is superior to the AWD eTV model in this test. One reason to this behaviour could be how the torque vectoring systems are working. Since the eTV has the ability to provide negative torque for the inside wheel and positive torque for the outside wheel, this could be a disadvantage in a low-friction situation, as there would be a higher risk of oversteering. That is observed when the model is ran on a road with 0.43 coefficient of friction. Having said that, the vehicle oversteers and loses control completely with this friction level, whereas with a coefficient of 0.44, the vehicle is very stable and shows no under- or oversteering. This change of behaviour by only increasing the coefficient by an increment of 0.01 is unexpected and poses questions as to how sensible the eTV system is to different situations.

### 5.3 Track 3 - Hällered's test track

Vehicle configuration	Energy consumption (KJ/m) at 120 km/h
AWD TVDC (3.4.1)	228.6
AWD eTV (3.4.3)	224.6
AWD eTV-control logic (3.4.4)	224.5
RWD TVDC (3.4.6)	229.5
RWD open diff (3.4.5)	225.2

Table 5: Energy consumption on Hällered track with Volvo XC90

As seen in the table above, the AWD eTV model is the most efficient in this test. That means that it manages to distribute the torque in the most efficient way to provide the lowest energy consumption, which doesn't come as a surprise as it has the most advanced torque vectoring system. Worth adding that the control logic in the AWD eTV model added an ever so slightly lower energy consumption. The difference is very small to draw the conclusion that a control logic is a must for a more efficient model but it does indicate that developing a more advanced control logic can probably add even more benefit to the efficiency.

What can also be noticed here is that the AWD models had lower energy consumption than the RWD TVDC model. One might think that the added weight of an AWD configuration results in

worse efficiency but what this test shows is that the torque vectoring system together with the added traction in the front results in better efficiency. This also depends on the type of track used. This was a handling track meant to test the handling of the vehicles, so it put the torque vectoring system into play. If it would have been a track that simulates city driving with lower speeds, and more uphill, then the weight would have played a bigger role than the behaviour of the torque vectoring system.

Comparing the RWD TVDC and open-diff models, the model with the open-diff was superior and had lower consumption. The explanation to that might be that the open-diff is one of the simplest forms of differentials and in comparison to the TVDC system it doesn't have clutches nor a control system. This means that there are fewer friction and heat losses and less weight, which improves the efficiency. However, this doesn't disregard the fact that with more tuning, lower energy consumption and better efficiency can be obtained with the TVDC.

## 5.4 Variable time plots at the downhill track

The plots in the coming section show the variation of the tested variables' values against distance for the Volvo XC90 in two configurations; TVDC-AWD and eTV-AWD on the downhill track. All the plots are going to be analysed and interpreted.

### 5.4.1 Longitudinal acceleration

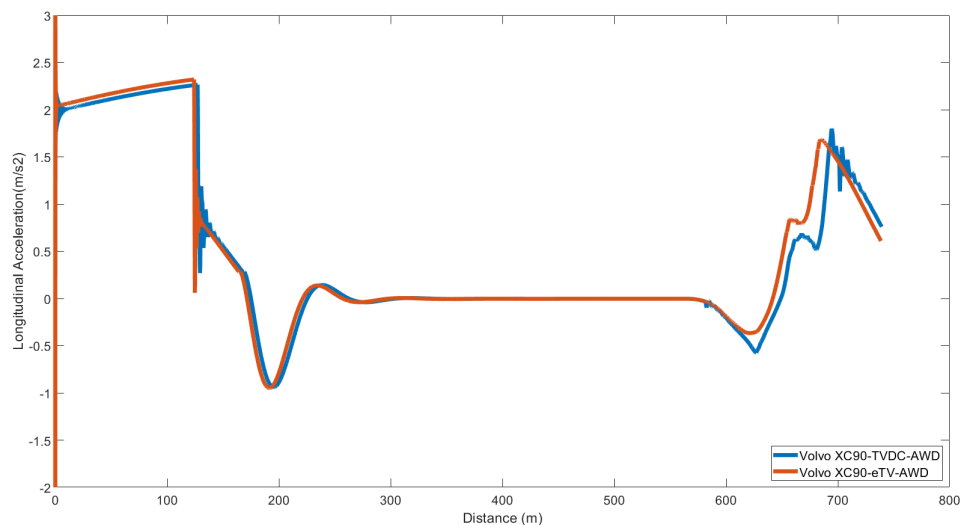


Figure 26: Longitudinal acceleration

It can be seen that the longitudinal acceleration in figure 26 for the AWD TVDC and eTV overlap and behave the same way up during the course of the track, with the eTV curve occurring slightly before the TVDC curve which suggests that the eTV model has less delays modelled. That is deemed to be reasonable as both models have delays but the delays caused by the extra motor in the eTV system are probably smaller than the delays caused by the clutch application in TVDC. In other words, the clutches have more friction and heat losses, which can cause the observed delays.

### 5.4.2 Lateral acceleration

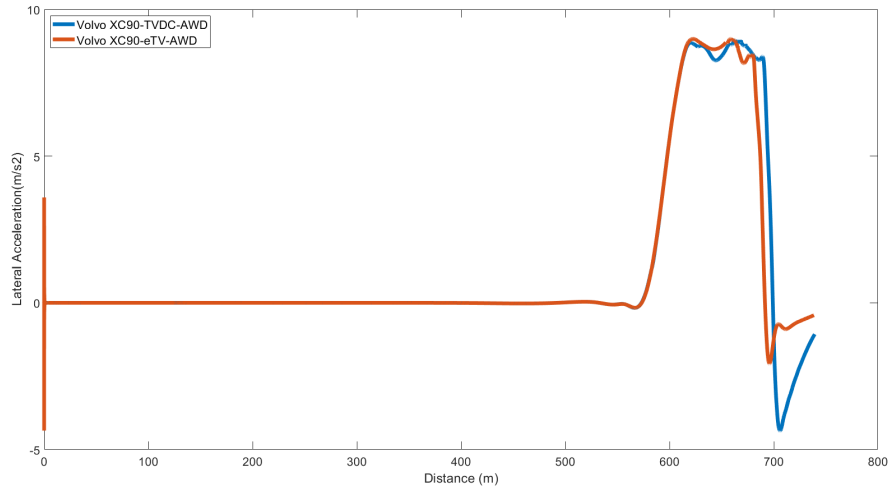


Figure 27: Lateral acceleration

For the lateral acceleration in figure 27 we can see again that the curves for both the AWD TVDC and eTV models have the similar shape. The major difference between the two is observed near the end of the end track where the AWD TVDC model experiences a higher negative lateral acceleration than the eTV model. That means that the vehicle is experiencing a higher variance when recovering from the understeer that it had. This might indicate that the yaw rate is higher, since the equation for lateral acceleration in steady state cornering is as following:

$$a_y = \omega_z \cdot v_x \quad (16)$$

Where  $a_y$  is the vehicle's lateral acceleration,  $\omega_z$  is the yaw rate and  $v_x$  is the vehicle speed. With the vehicle's velocity being the same for the two models as well as the  $a_y$ , the higher yaw rate explains the higher lateral acceleration.

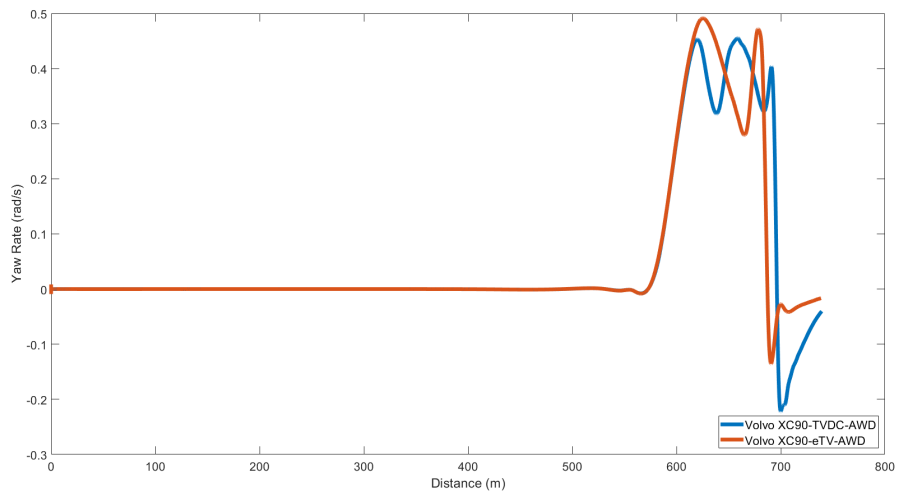


Figure 28: Yaw rate

Looking at figure 28, the yaw rate is indeed higher towards the end of the curve. This suggests that the TVDC system is intervening more aggressively than the e-TV system in order to correct the understeering.

### 5.4.3 Longitudinal slip

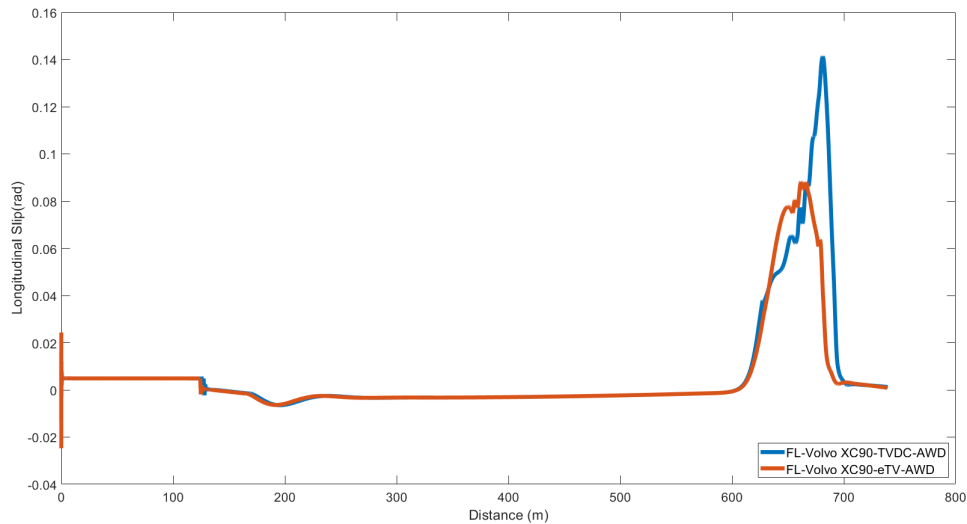


Figure 29: Longitudinal slip of the front left wheel

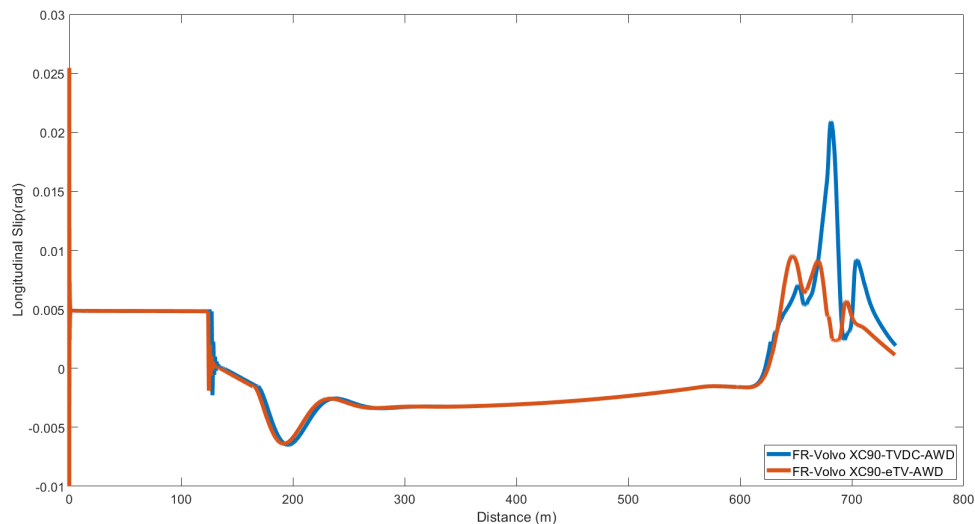


Figure 30: Longitudinal of the front right wheel

Looking at the longitudinal slip at the front wheels in figure 29 and 30, the slip is positive for the models in the beginning which is expected as the vehicle is doing a hard acceleration to get up to speed. It can be noticed though that during the cornering the TVDC model exhibits

a considerably higher slip which might indicate that this configuration is understeering more. Taking into consideration that both AWD models have the same setup in the front axle and the same torque, a deeper look has to be taken into the longitudinal slip equation.

$$Slip = \frac{R \cdot \omega - v_x}{v_x} \quad (17)$$

with  $v_x$  being the velocity's longitudinal component of the wheel hub, omega being the rim rotation speed vehicle and R being the effective rolling radius of the tire. The higher slip seen in the plots indicate that the difference between  $v_x$  and  $R \cdot \omega$  in the TVDC model during cornering is higher.

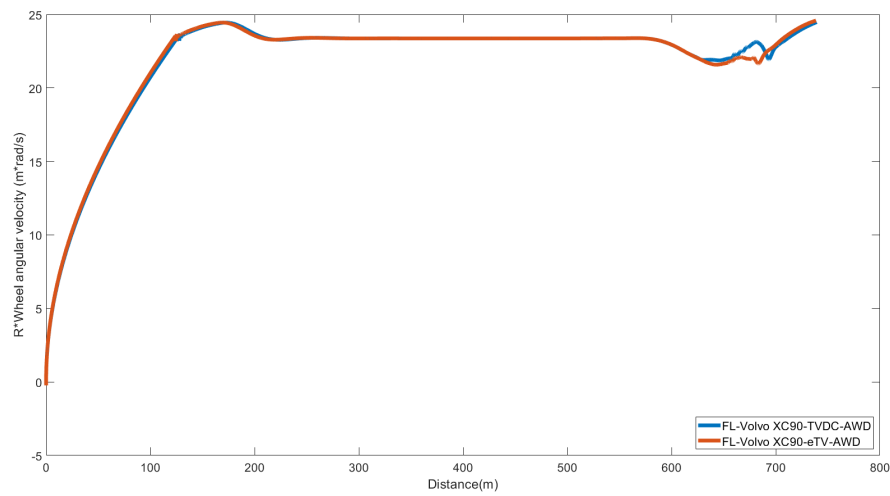


Figure 31:  $R \cdot \omega$  of the front left wheel

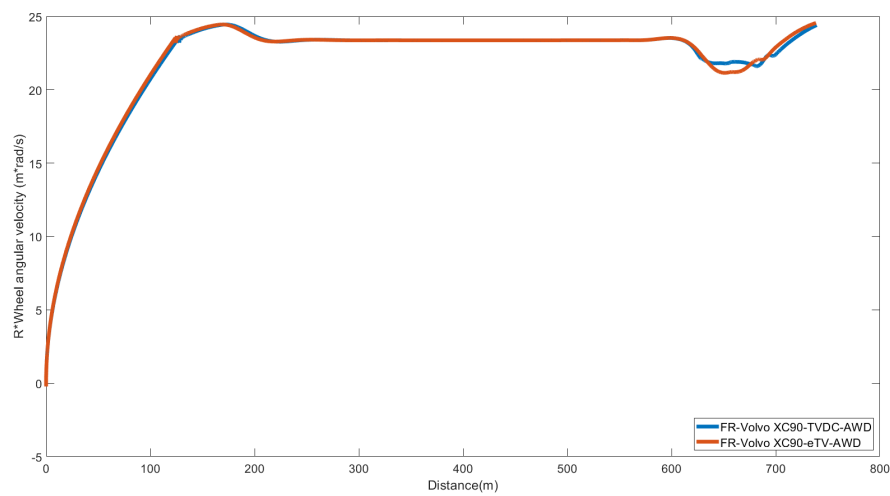


Figure 32:  $R \cdot \omega$  of the front right wheel

Upon checking the plots for  $R \cdot \omega$  in figure 31 and 32 at the front and left wheel for both models, the value is higher for the TVDC model. Checking the wheel hub velocity plot in CarMaker shows that the TVDC model has a lower velocity than the e-TV model during the cornering phase. With a lower velocity and higher angular speed, the difference between the quantities is higher than that of the TVDC, thus the slip value is higher. Assuming that the torque at the front axle is the same in both models, this might then be due to that the rear axle is giving out more torque which makes the front axle slip more.

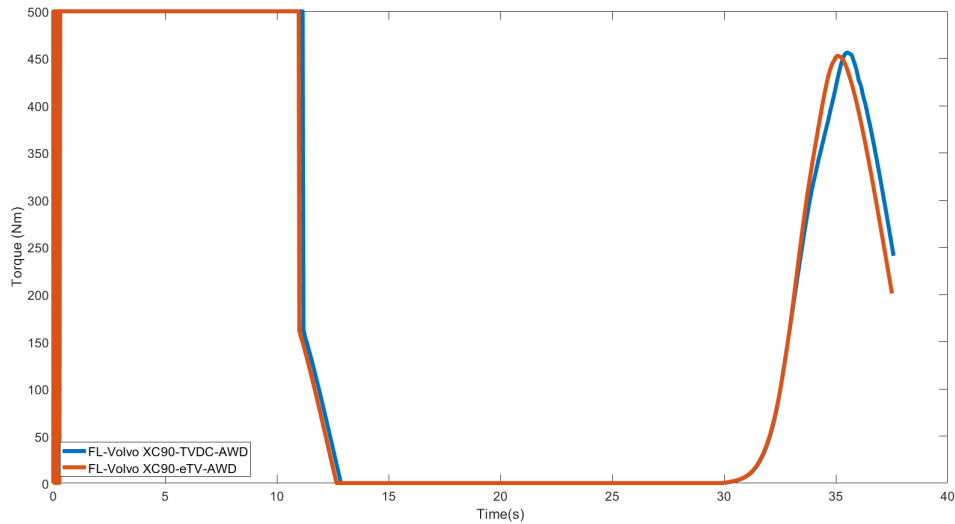


Figure 33: Torque at the front left wheel

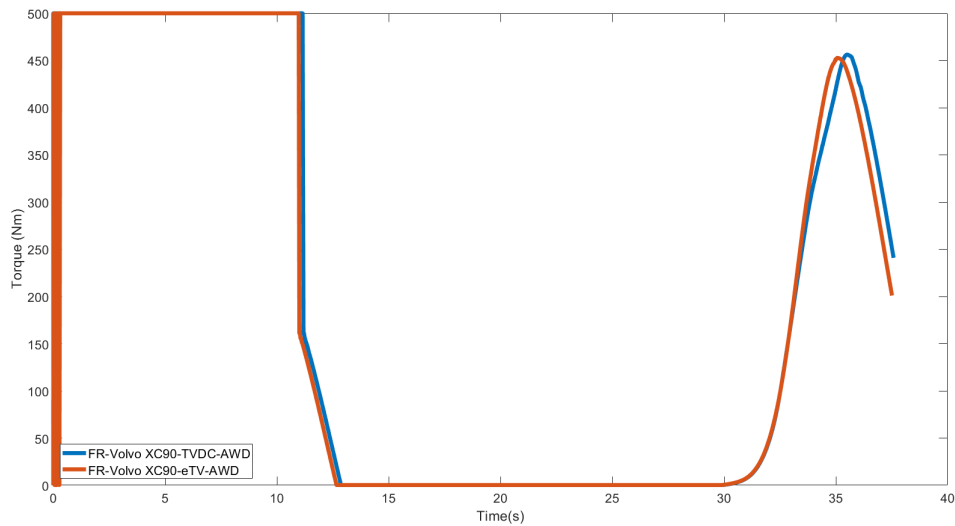


Figure 34: Torque at the front right wheel

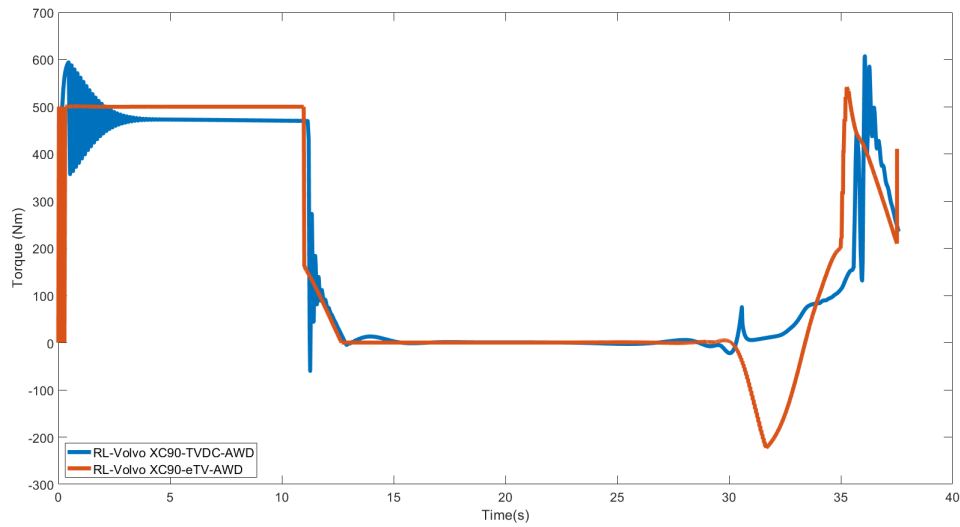


Figure 35: Torque at the rear left wheel

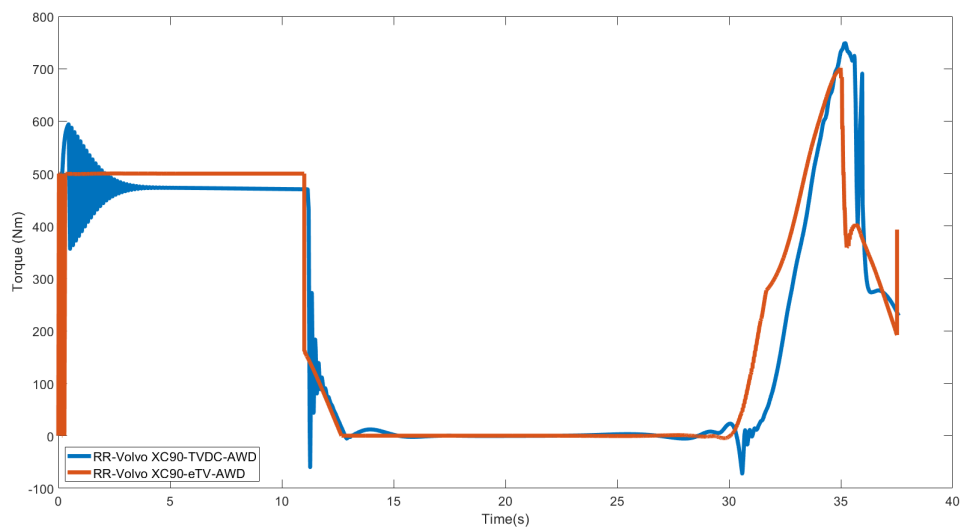


Figure 36: Torque at the rear right wheel

Looking at the torque plots at the front axle in figure 33 and 34, the values have the same magnitude. At the rear axle, as seen in figure 35 and 36 it is evident that the TVDC model is giving out a higher torque than the eTV model.

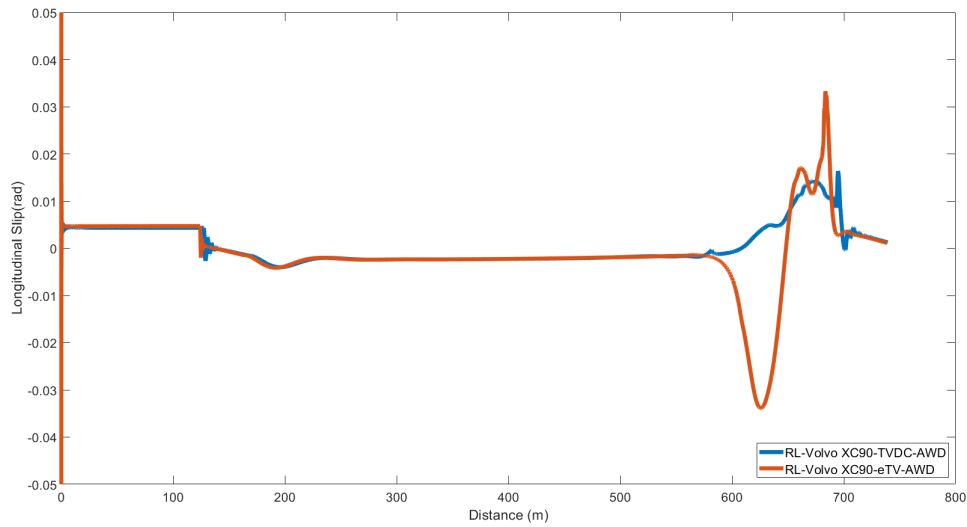


Figure 37: Longitudinal slip of the rear left wheel

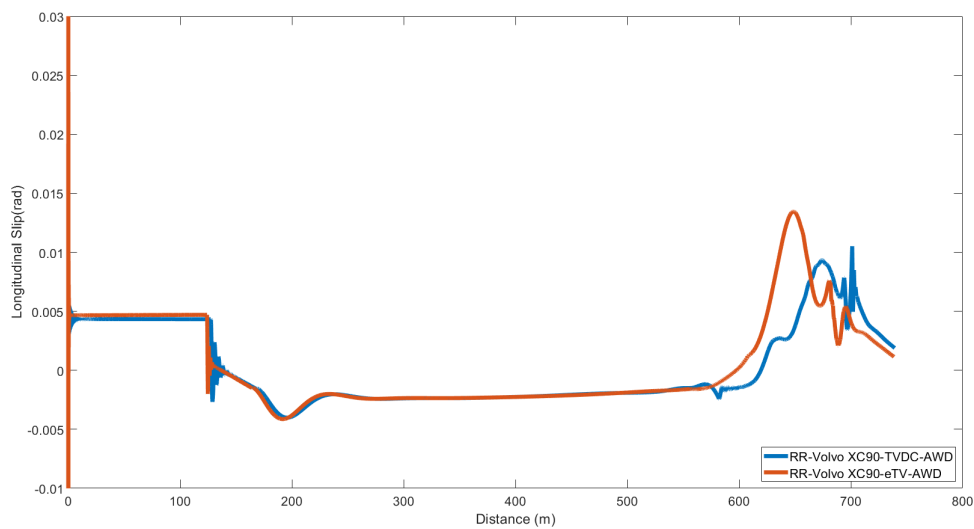


Figure 38: Longitudinal slip of the rear right wheel

Looking at the slip in the rear axle in figure 37 and 38, in the rear left wheel there is a noticeable negative slip in the e-TV model. That implies that the torque vectoring system might be applying negative torque on this wheel with the help of the small extra motor that it has, to help the car navigate the corner better and stay on course. That is confirmed by the torque plot in figure 35. This can also explain why the e-TV model is able to manage the course at a higher intended speed than the TVDC model. Looking at the rear right wheel, the slip is positive and the highest in the e-TV model. In other words, the combined positive slip in the rear right wheel and negative slip in the rear left wheel creates a higher yaw moment around the center of gravity which helps the car turn better.



#### 5.4.4 Side slip

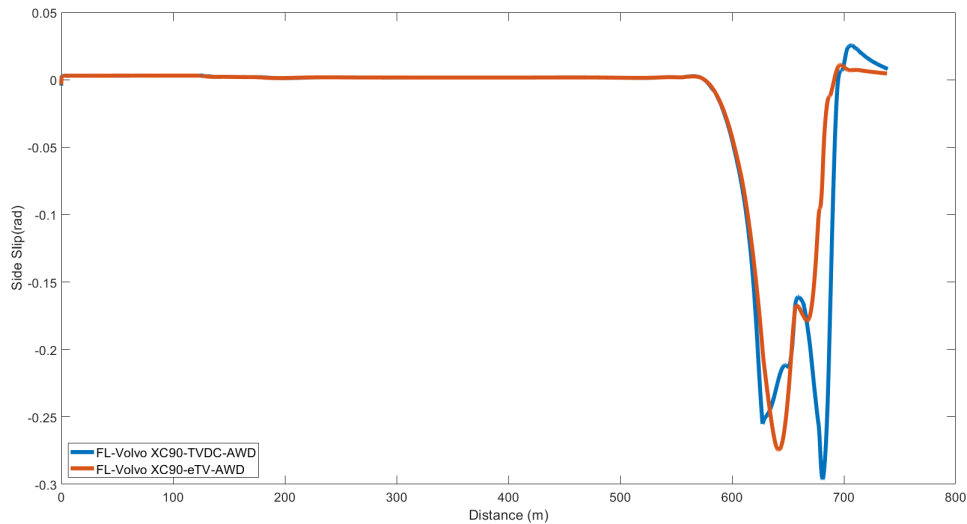


Figure 39: Side-slip of the front left wheel

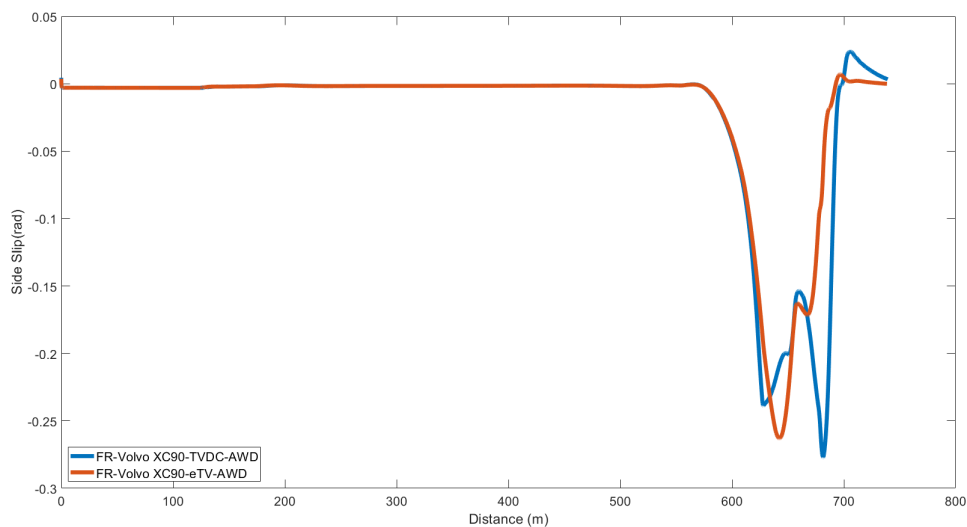


Figure 40: Side-slip of the front right wheel

When it comes to side slip, there is a noticeable side slip in the front axle in the models as seen in figure 39 and 40, which is expected since there is a heavy understeering pushing the car out of its intended path. It can be seen that the negative slip in the TVDC model displays a strange behavior as it increases in the beginning of the curve after 600 meters then decreases through the curve to increase again sharply. This might suggest that the steering angle is not being constant throughout the curve, and a higher angle is being applied again towards the end of the curve.

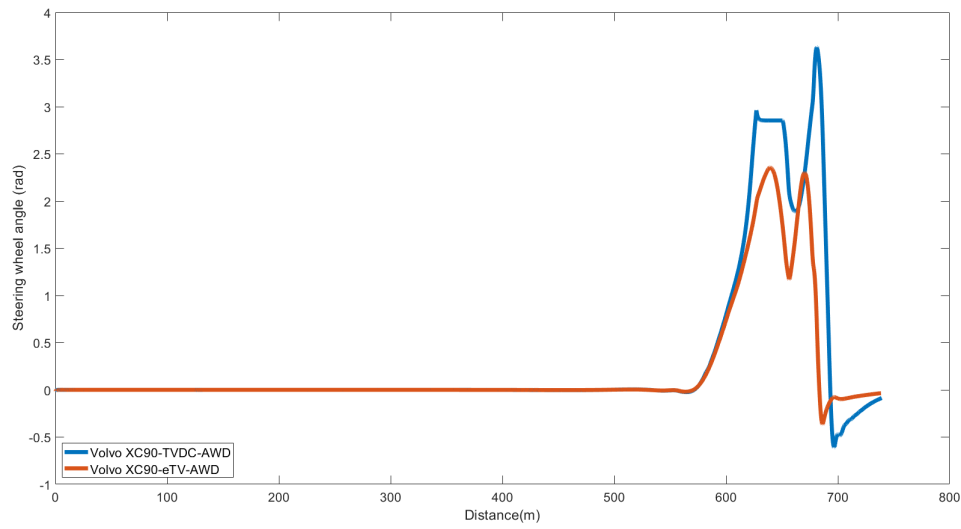


Figure 41: Steering wheel angle

Looking at the steering angle plot in figure 41 it is evident that more steering is applied during the cornering. The reason as to why more steering is applied might be to keep the vehicle on the track as the heavy understeering is pushing the vehicle to run off-course.

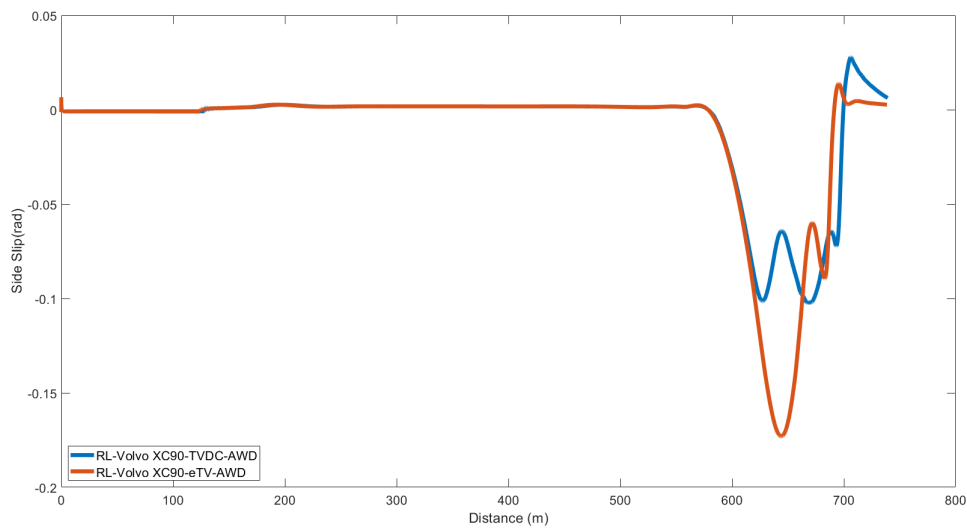


Figure 42: Side-slip of the rear left wheel

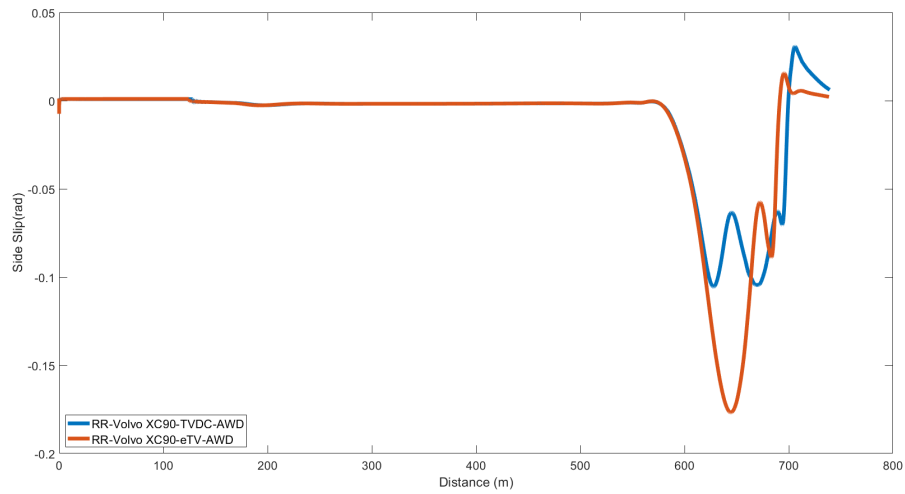


Figure 43: Side-slip of the rear right wheel

Regarding the rear axle, it can be seen in figure 42 and 43 how the eTV model exhibits the highest negative side slip while cornering. This suggests that the rear end of the vehicle is being pushed outwards more, which might help the car to orient itself along the curved road better. The understeering makes the vehicle less yaw responsive, so the car's orientation along the curved road might be worse. To make the car stay laterally on the curved road, both side slip front and rear have to be limited. To make the car stay orientated along the curved road side slip front and rear have to be balanced against each other.

#### 5.4.5 Yaw

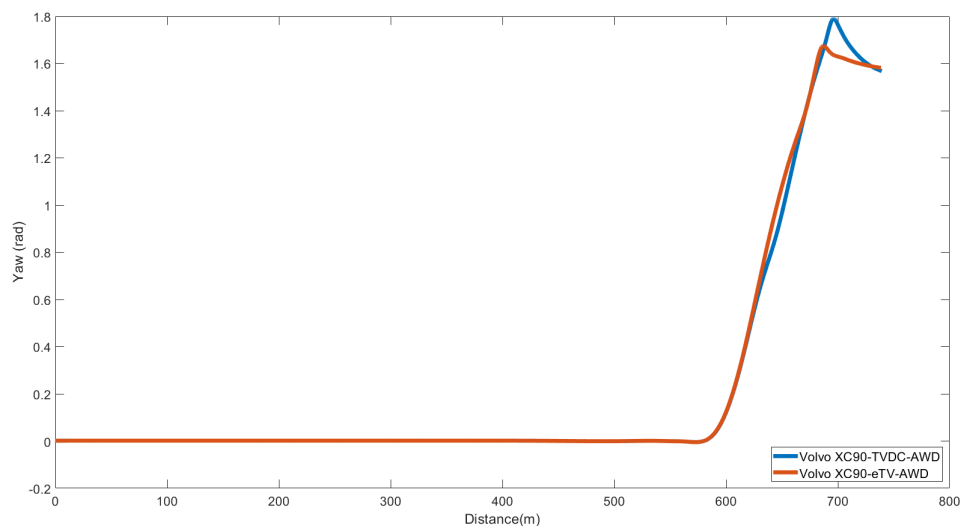


Figure 44: Yaw

The yaw, shown in figure 44, achieves a higher peak in TVDC model but a lower yaw rate, shown in figure 28 which suggests again that it undergoes a larger understeering, thus less yaw responsive than the e-TV model which has a lower yaw but higher yaw rate. The e-TV model would then be felt more twitchy but zippier which indicates that it is more sensitive to the steering input and can navigate the corner with a higher speed. This is actually the case when looking at the maximum entry speed test.

### 5.5 Variables' time plots at the slalom track

Firstly, it is worth noting that upon looking at the simulation movies the AWD TVDC model was exhibiting more understeering in the curves, as it was considerably closer to the edge of the road compared to the e-TV model, as shown in figure 45 and 46 below.



Figure 45: Understeering of TVDC model



Figure 46: Understeering of e-TV model

### 5.5.1 Lateral acceleration

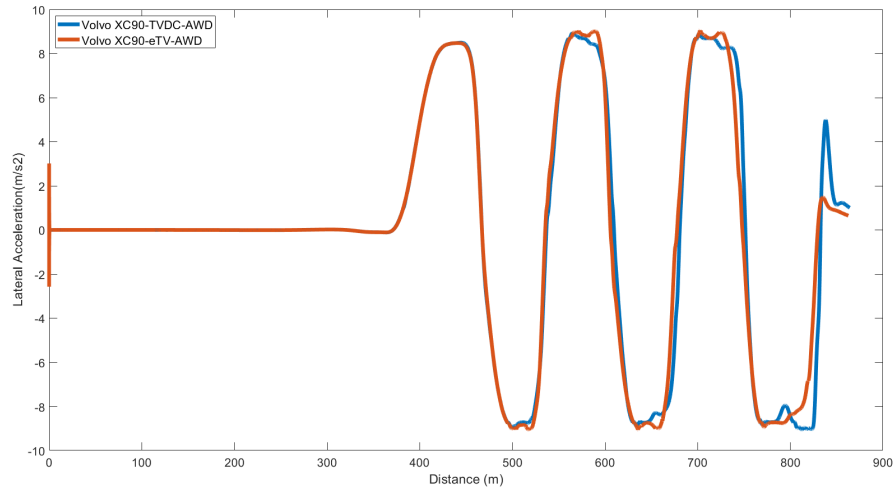


Figure 47: Lateral acceleration

Not much difference is seen in the lateral acceleration between the two models when looking in figure 47, until the last curve of the track where the AWD TVDC model exhibits a higher lateral acceleration which suggests that the model might be slightly oversteering when stabilizing itself at the last straight segment of the track. This is the same behaviour observed in the previous comparison on the downhill track and is also due to the higher yaw-rate seen in figure 57.

### 5.5.2 Longitudinal slip

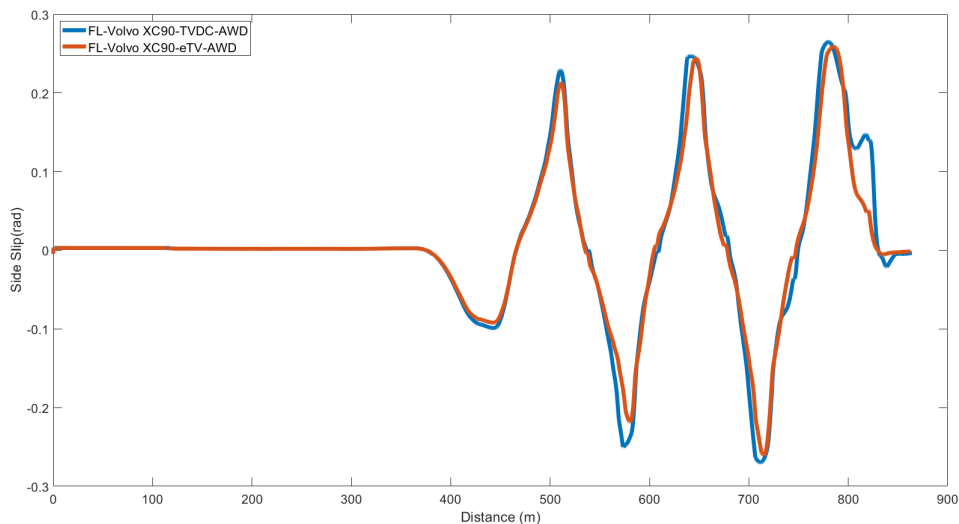


Figure 48: Side slip of the front left wheel

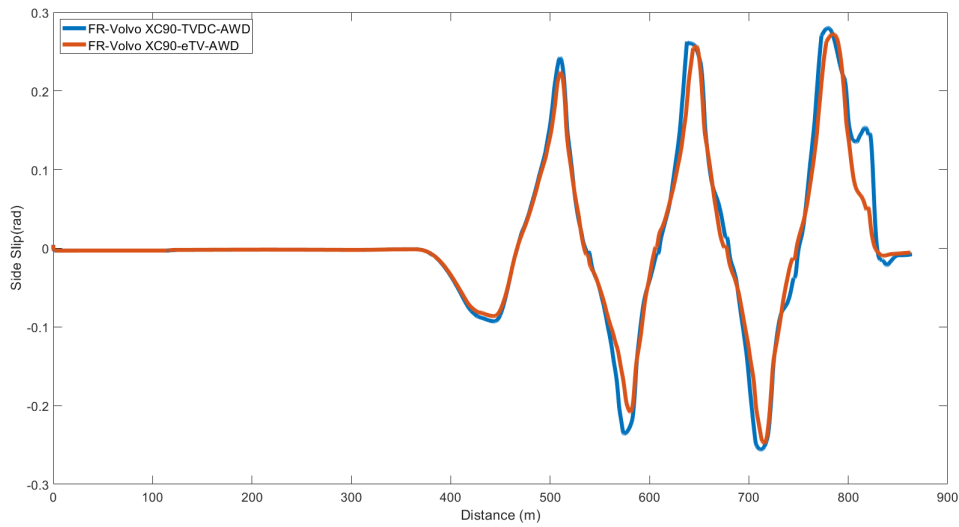


Figure 49: Side slip of the front right wheel

The side slip in the front axle, shown in figure 39 and 49, is again slightly higher in this case for the TVDC model, which suggests that it is subjected to more understeering. Something that is noticed when looking at the simulation movies.

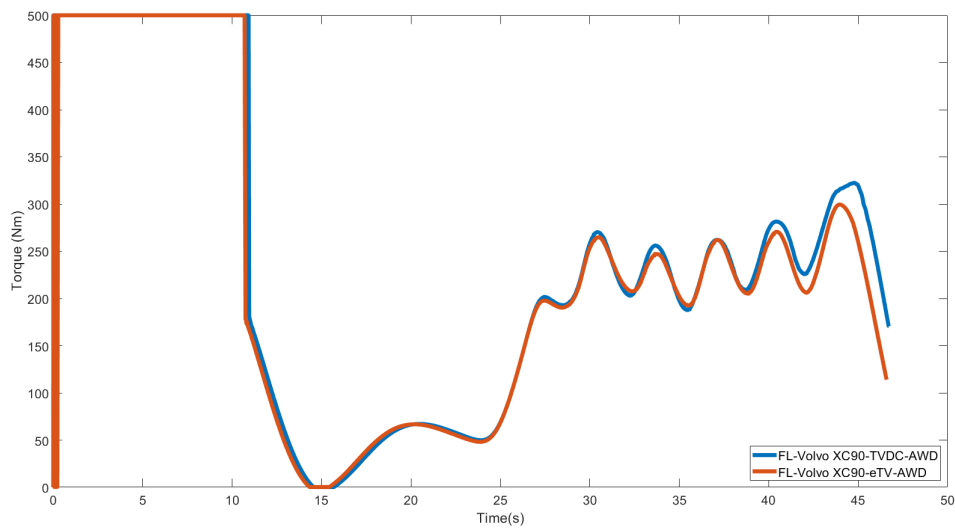


Figure 50: Torque of the front left wheel

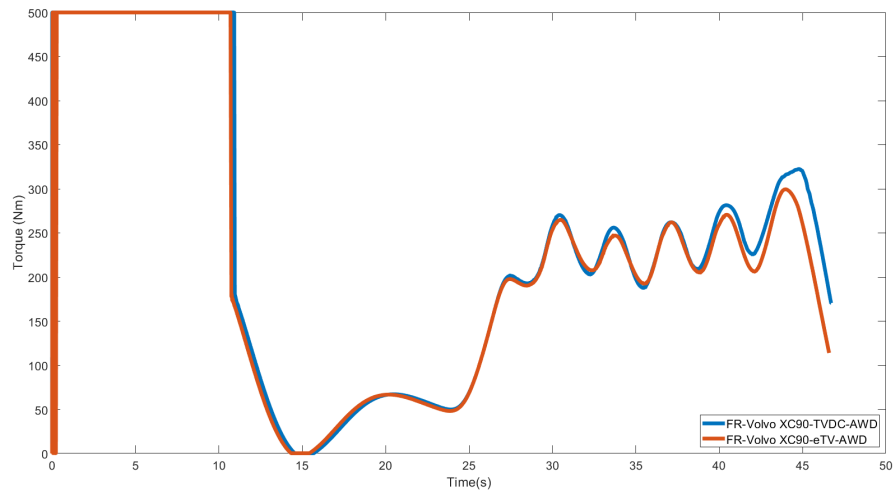


Figure 51: Torque of the front right wheel

Trying to understand why it is happening, it is worth looking at the torque in the front axle shown in figure 50 and 51. It can be directly noticed that the torque for the TVDC model is slightly higher. The reason as to why it is higher is unknown as the setup in the front is the same for both models. Thus, it is an interesting phenomena.

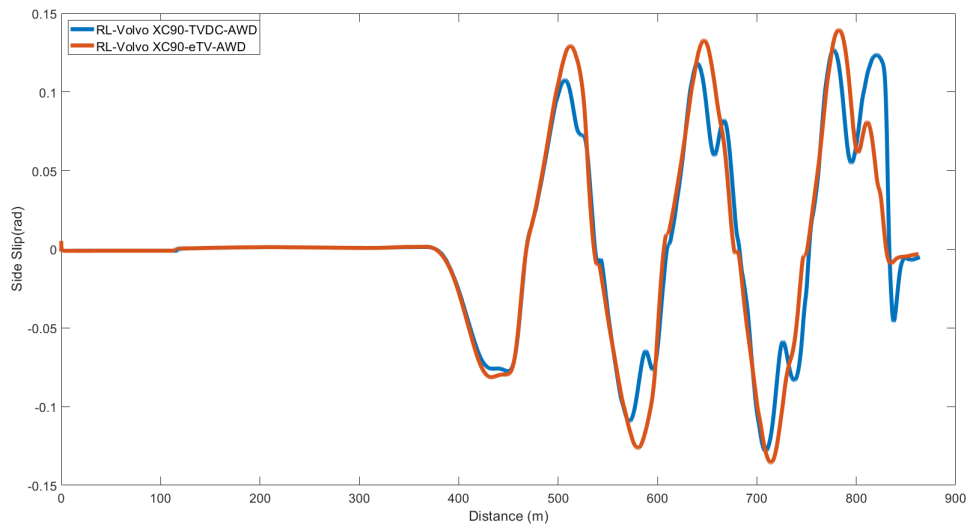


Figure 52: Side slip of the rear left wheel

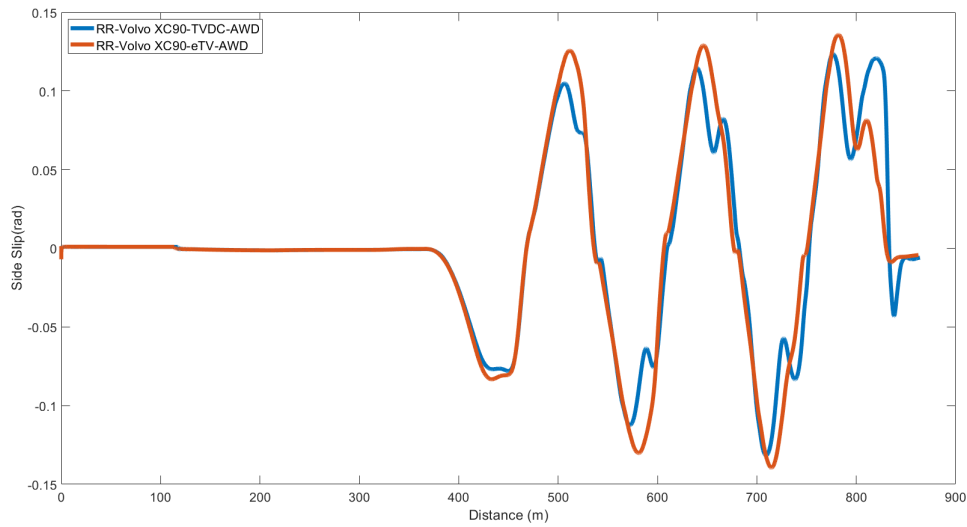


Figure 53: Side slip of the rear right wheel

Regarding the longitudinal slip at the rear axle, as seen in figure 52 and 53, the same behaviour is again noticed with the higher positive and negative slip in the eTV model, suggesting that the model's rear-end is more susceptible to oversteering, which confirms what is observed on the downhill track.

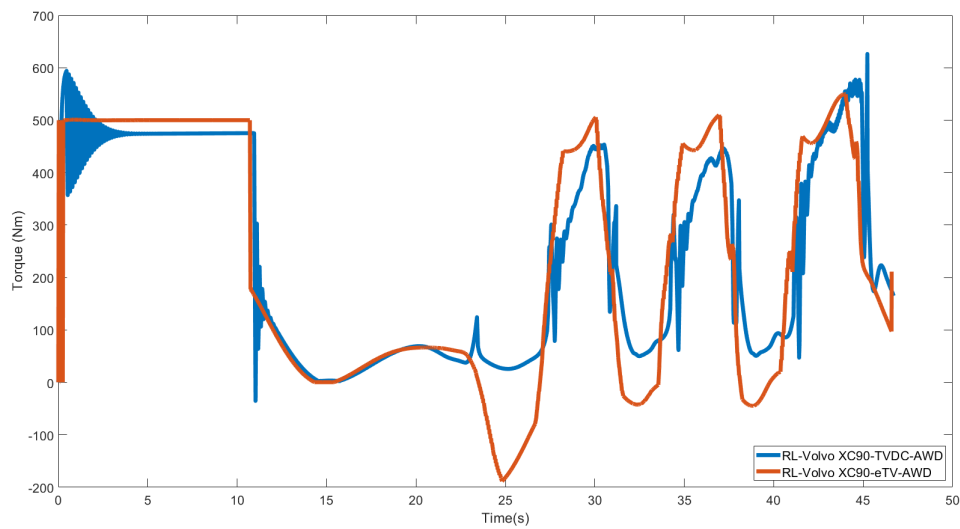


Figure 54: Torque of the rear left wheel



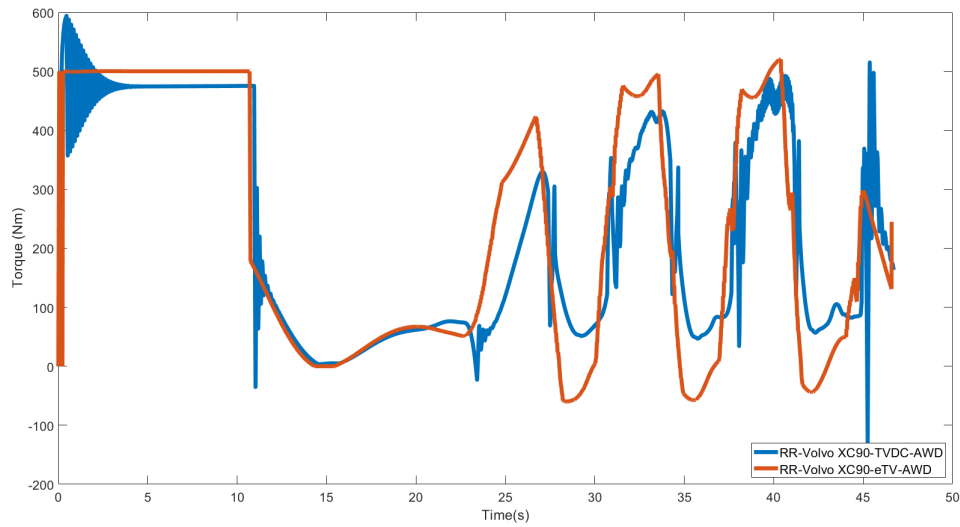


Figure 55: Torque of the rear right wheel

Upon looking at figure 54 and 55, when it comes to the torque at the rear axle, the eTV model has a negative torque on the inside wheel and a higher positive torque on the outside wheel. Thus, the side slip and the torque confirms what is explained previously that the eTV model exhibits a higher yaw moment.

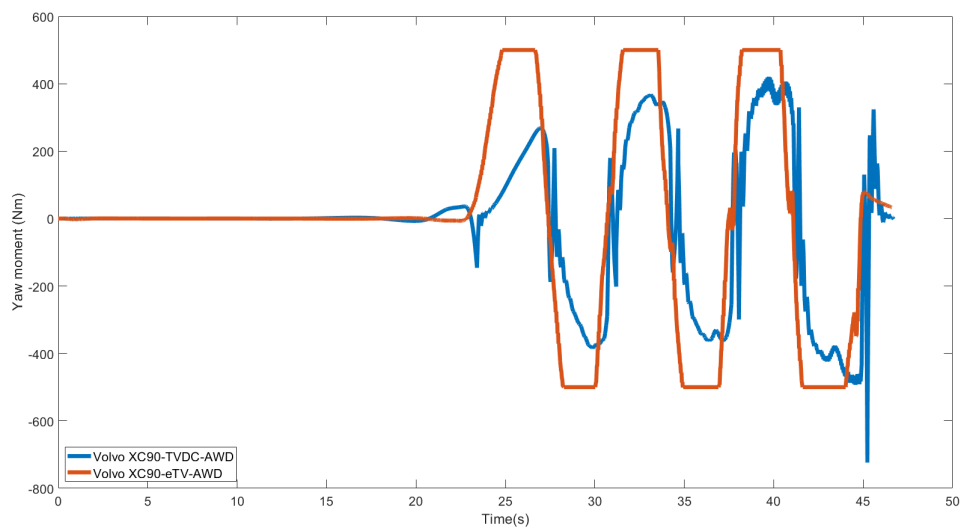


Figure 56: Yaw moment

Taking a look at figure 56, the amplitude of the yaw moment is indeed higher in the eTV model. Something that should help in better navigating the corners.

### 5.5.3 Yaw rate

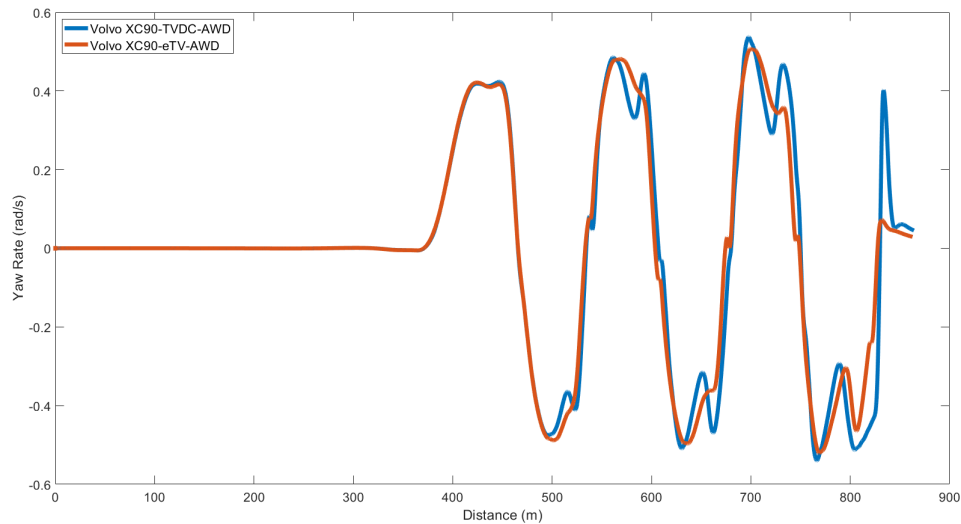


Figure 57: Yaw rate

The yaw rate shown in figure 57 is very similar for the two models in the first segment and curve of the track. In terms of magnitude there isn't a significant difference between the models, apart from the fact that during the last three curves the AWD TVDC model exhibits a higher magnitude. This most probably depends on the larger understeering experienced by this model as it approaches the end of the track, as observed in the simulation movies. The biggest difference lies though in the shape of the yaw rate curve. It can be seen that the yaw rate of the eTV model changes somewhat constantly through a curve, whereas for the TVDC model, the magnitude reaches a maximal amplitude, decreases then increases again. This suggests that the steering applied isn't constant, and more steering is being applied during the cornering phases. This behaviour is similar to and confirms the one seen and explained on the downhill track.

## 6 Conclusion and Future Work

### 6.1 Conclusion

The first objective of modularity of subsystems on a virtual test environment was achieved through this project. This means that all the subsystems in the built up library can be exchanged to design multiple desired configurations. This will help in bringing down the testing times drastically and improve the flexibility for virtual verification of any given configuration.

Also, the second objective is met, through that the defined tests with measure can be used to compare the vehicles with different configurations of axles (front and rear) and hence different vehicle propulsion torque control.

In the given time-frame, several configurations have been modelled and simulated in a virtual test environment which accounts for the vehicle dynamic performance and the energy consumption of the drive axle. On comparing these configurations, the AWD with e-TV on the rear axle had superior performance, in terms of both longitudinal and lateral dynamics. It also consumed the lowest energy when compared with all the given configurations.

### 6.2 Future Work

In this project, the focus was on arriving at the numbers and achieving modularity. But, does this mean that the numbers are good enough for correlation with real-life test results? No. The basic control logic used during the development of libraries for subsystems need to be improved to include

- Torque distribution by improving the vehicle's control system
- Control of longitudinal wheel slip
- Improved torque vectoring for all manoeuvres
- Regenerative braking and advance braking systems (ESC)

On improving the control logic, the results obtained through virtual verification can be correlated with actual driving test results. This correlation will help in improving the model libraries. Another thing that could potentially be studied is to make an optimization of the requested time trajectories(optimal control). That would be a way to find out the absolute potential of a propulsion system without having to try different controllers.

By building an advanced (complex) controller into the model, the simulation time will increase drastically. In that case, the simulation time can be improved by converting multiple blocks in simulink to a single executable block or a C-code within CM [9]. If needed, the parameterization for the individual blocks can be done while creating the executables, similar to what has been done with parameterization in FMUs.

Furthermore, other subsystems, for example the powertrain and the battery system modelling can be modelled to achieve a complete vehicle library on a virtual environment which can be used for simulation.

## References

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## A Appendix

### A.1 Additional Parameters- CM Setup

OpenXWD standalone needs additional powertrain parameters that are defined to initialise the simulations. In CarMaker window, vehicle settings- Additional, the functional parameters are defined as shown in the figure, used while FMU/Simulink Plug-in [9]. The *parametersPowerTrain.PTKind* = BEV define the powertrain models, similarly the type of clutch and gearbox is specified as in figure 58.

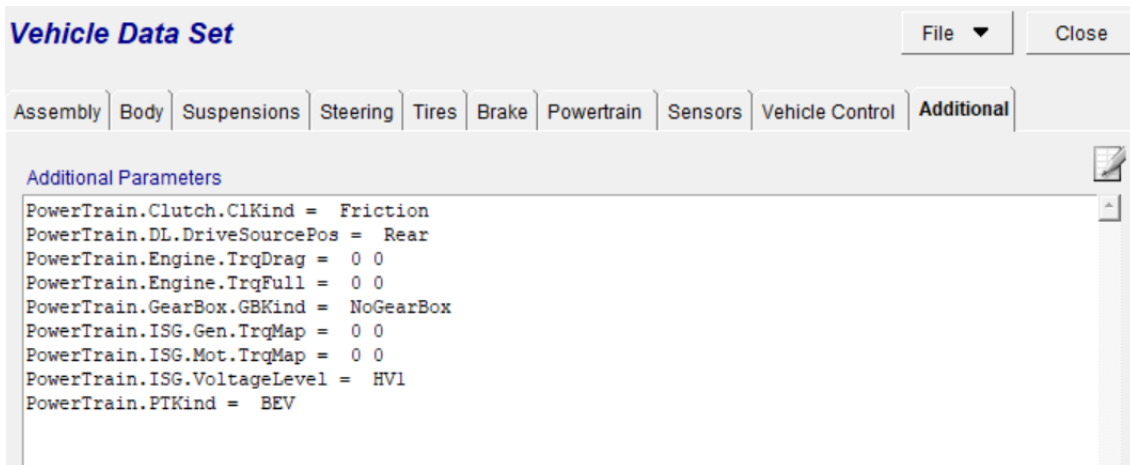


Figure 58: Additional parameters

### A.2 Dymola License Setup

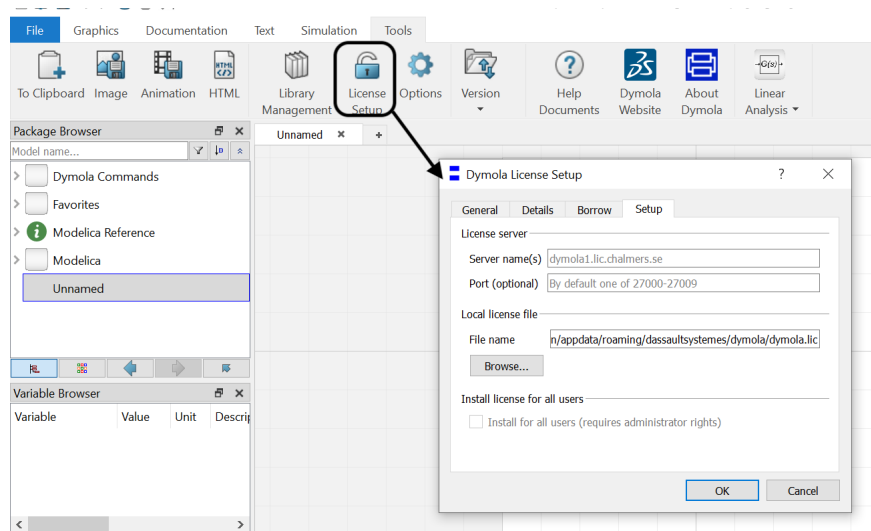


Figure 59: Dymola license setup window