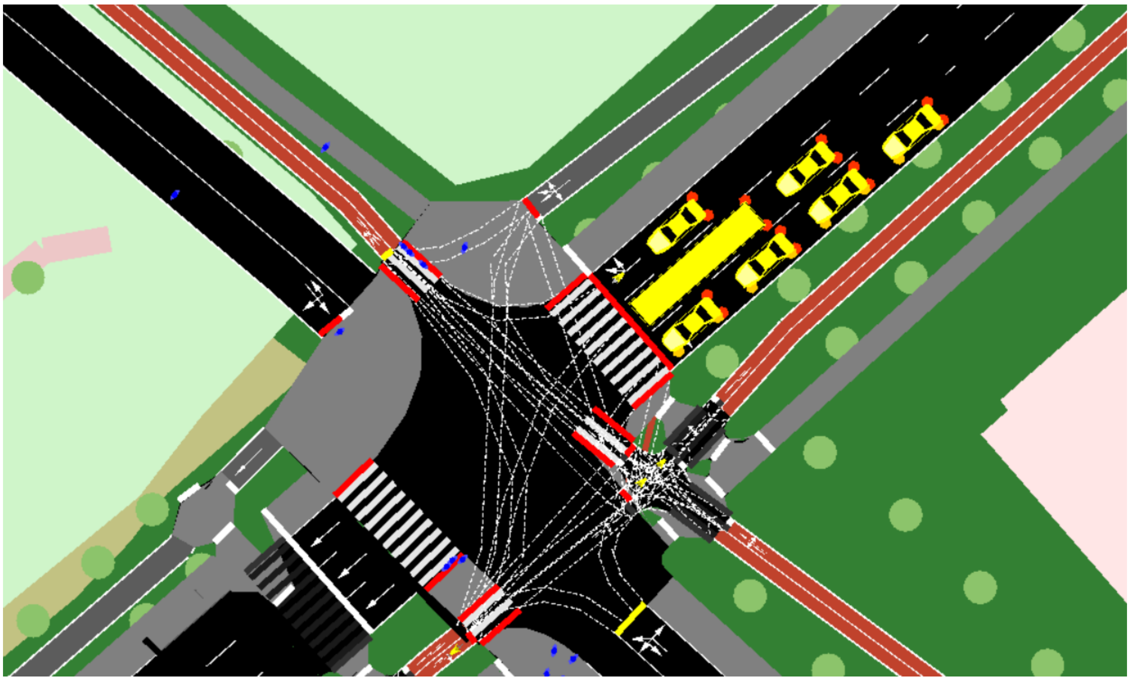

Driver and Traffic Impact on Battery Electric Vehicle Driving Range

Master's thesis in Automotive Engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Master's thesis 2020:67

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Satish Kumar Gouda, Gothenburg, December 2020

Abstract

The energy consumption and driving range of a Battery Electric Vehicle (BEV) is determined from tests on a chassis dynamometer under standardized conditions. However, when a customer is driving his/her car on the road, the energy consumption and range may be significantly different due to many factors, such as driving style, ambient conditions, road, traffic, etc. The aim of the thesis work is to develop a method for analyzing the impact of various traffic situations, and driver behavior on electric vehicle's driving range. In order to capture real world traffic situation and driver behaviour, a virtual road network of rural, urban and motorway road segment picked from CEVT defined real world driving route was created in SUMO. Driving cycle obtained from traffic simulation in SUMO were fed manually to CEVT built vehicle model in CarMaker. Post process script was written in Python to extract the result for the simulation. A new method to capture the effect of traffic and driver behaviour was implemented and it was found that mainly traffic situations and driver behavior had impact on energy consumption and range of BEV.

Keywords: Battery Electric Vehicle, Energy consumption, Traffic situation, driver behaviour, SUMO, CarMaker.

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Introduction

1.1 Background

Traditionally the energy consumption and driving range of a vehicle is determined from tests on a chassis dynamometer under standardized conditions, for example, NEDC (New European Driving Cycle) and WLTP (Worldwide harmonized Light-duty Vehicles Test Procedure). However, when a customer is driving the vehicle on the road, the energy consumption and range may be significantly different due to many factors, such as driving style, traffic flow, weather and road conditions, etc. The thesis work aims to develop a method for analyzing the impact of various traffic situations and different driver behaviour on an electric vehicle's driving range.

1.2 Aim

The primary goal of the thesis work is to develop a method to enable analysis of the impact of driver behavior and traffic situation on the Battery Electric Vehicle (BEV) energy consumption. For this study case, the aim is to investigate how much the energy consumption changes when driver aggressiveness (rapid acceleration and deceleration), traffic density, and traffic flow factors are varied. Further, to determine which factors are most important to focus on in future development work.

1.3 Scope

The scope of the thesis work is to investigate the effect of real-world traffic situation and driver behavior on energy consumption and identify traffic simulation tools that is capable of modelling pedestrians, public transport, lead vehicles, and build a virtual traffic network of real drive route defined by CEVT. Define a method on how to use traffic simulation tools along with the vehicle model built-in Carmaker, followed by writing a post-process script in Python to extract the results from the simulations, these results are further analyzed to determine the effect of traffic situation and driver behavior factors on energy consumption and make recommendation for future development work.

1.4 Thesis layout

A schematic representation of thesis layout is shown in the Figure 1.1. The work is broadly classified in to two blocks: traffic simulation and vehicle simulation. In the traffic simulation block, traffic scenarios and driver behaviour are fed to traffic model which consists of virtual road network. The simulations are then carried out and output of the simulation which consists of travel information of the Ego vehicle. This information is fed to data extraction script, where speed profile (Drive cycle) with the time step of one second is extracted.

The main objective of the vehicle simulation block is to simulate the vehicle model with speed profile from the traffic simulation block as input, the post processing script is then used to extract results from the simulation. Both the blocks are coupled synthetically where data is transferred manually between the simulation blocks. Here in this work data in the form of Speed profile is manually transferred from traffic simulation block to vehicle simulation block.

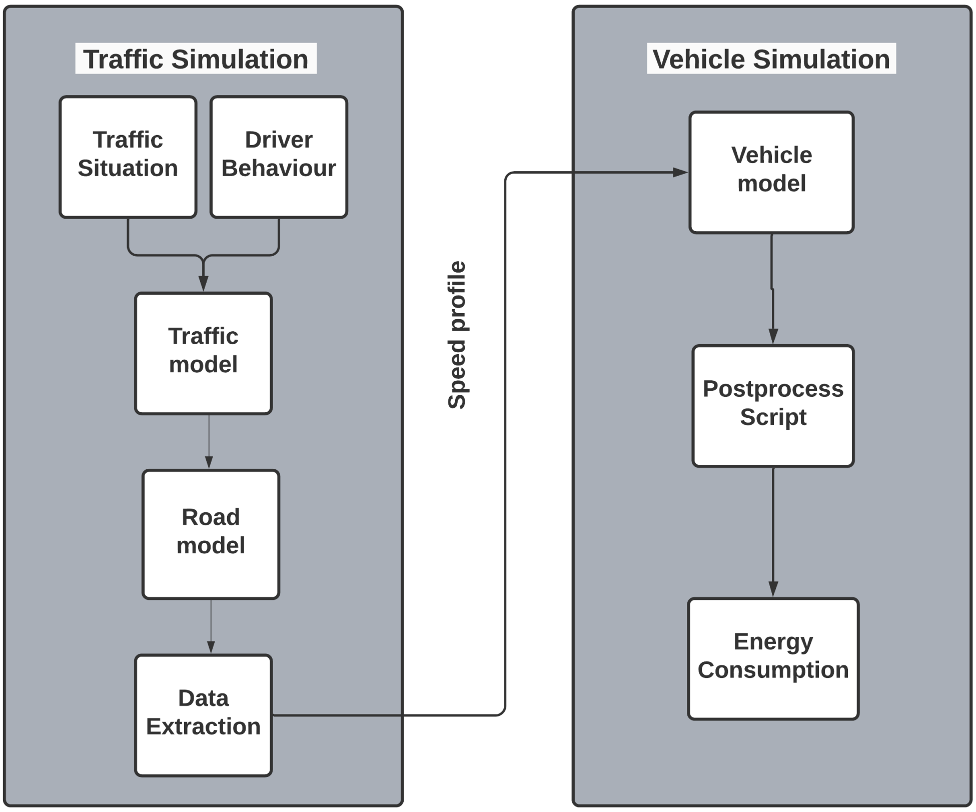


Figure 1.1: Thesis layout

1.5 Limitations

- Steering loss were not taken into consideration since the ego vehicle in Carmaker was driven on a straight road.
- In order to decrease the complexity of creating altitude profile in both simulation environment and also due to inaccurate elevation data of the road, the road segment were assumed to be flat.
- In order to reduce the complexity and prioritizing the other real world factors, pedestrians and public transport were assumed to be constant for all the cases in the respective road segment.

1.6 Research questions

- How much does the energy consumption vary when driver behaviour and traffic situation factors are changed ?
- Which factors are most important to focus on in future development work ?

2

Theory

2.1 Vehicle Energy losses

The propulsion or the traction force F_{trac} in a BEV is solely produced by Electric motor. In order to set a stationary vehicle in motion, traction force produced must overcome resistive force acting on the vehicle when moving on a particular terrain [14]. The amount of energy consumed to overcome the resistive force depends mainly on: aerodynamic losses, rolling friction losses and losses due to gravitational force. The longitudinal dynamics of the vehicle can be described using equation 2.3.

$$F_{\text{Net}} = F_{\text{Trac}} - F_{\text{Aero}} - F_{\text{Roll}} - F_{\text{Grad}} \tag{2.1}$$

From Newtons 2nd law

$$F_{\text{Net}} = m_{\text{veh}} a_{\text{veh}} \tag{2.2}$$

From equation 2.1 and equation 2.2

$$F_{\text{Trac}} = F_{\text{Aero}} + F_{\text{Roll}} + F_{\text{Grad}} + m_{\text{veh}} a_{\text{veh}} \tag{2.3}$$

Where F_{trac} is the traction force generated by electric motor, F_{Aero} is the aerodynamic drag, F_{Roll} is rolling resistance, F_{Grad} is the losses due to graivational force or losses due to road gradient acting on a vehicle driving on a inclined surface with the road inclination of α.

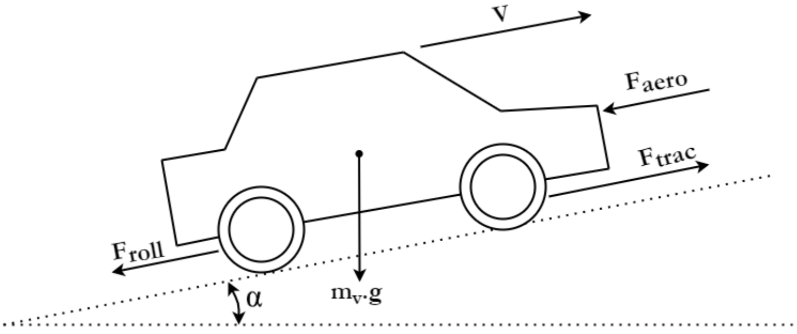


Figure 2.1: Force acting on the vehicle in motion

Schematic representation of various force acting on the vehicle in motion is shown in Figure 2.1.

2.1.1 Aerodynamic drag

The aerodynamic drag is a force acting in the opposite direction to the vehicle motion. The aerodynamic drag constitutes of two types of drag: Skin friction drag and pressure drag. Skin friction drag originates because of "the viscous friction between the air and the surface of the vehicle". Pressure drag originates because of the difference in front and rear end of the vehicle, when a vehicle is moving a high pressure or stagnation pressure is created in the front end of the vehicle since it is pushing the air out of the way, whereas on the rear end of the vehicle a hole is created as the vehicle moves forward which is known as wake. This region creates low pressure which sucks the vehicle in the opposite direction of vehicle motion. Greater the pressure difference in the front and rear end of the vehicle higher the drag force. For a typical passenger vehicle ratio of friction and pressure drag is 7% and 93 % respectively [23]. F_{aero} is given by,

$$F_{\mathrm{aero}} = \frac{1}{2}.\rho \, .c_{\mathrm{d}} \, .A_{\mathrm{f}} \, .v^2 \tag{2.4}$$

Where ρ is the density of the fluid(Air) through which vehicle travels, c_{d} is drag coefficient and it is a dimensionless quantity which is used to quantify the resistance of an object in fluid environment, A_{f} is the frontal area of the vehicle, v is the vehicle speed, it is evident from equation 2.4 that aerodynamic drag is proportional to vehicle speed and it increases with square of the vehicle speed.

2.1.2 Rolling resistance

The main contact between road and the vehicle is established by the wheels. There is a resistive force which resists the motion of the wheels when rolling on a surface. The wheels need to overcome this force to set the vehicle in motion, this force is known as rolling resistance. F_{Roll} is given by,

$$F_{\mathrm{roll}} = m_{\mathrm{veh}}.c_{\mathrm{r}}.gcos\alpha \tag{2.5}$$

$$F_{\mathrm{roll}} \approx m_{\mathrm{veh}}.c_{\mathrm{r}}.g \tag{2.6}$$

where m_{veh} is the mass of vehicle and it is directly proportional to rolling resistance , c_{r} is the co-efficient of rolling resistance which is dependent on vehicle speed and tyre pressure but these two factor do not vary significantly over the operating speed of the vehicle. So, in this thesis work c_{r} is assumed to be constant value. g is the acceleration due to gravity. cosα models the influence of the road inclination. However, as mentioned in section 1.5 the road profile is assumed to be flat, so cosα is neglected.

Figure 2.2 represents the general behaviour of aerodynamic drag and rolling resistance with respect to speed, it is worthwhile to notice that the aerodynamic drag increase with square of speed and rolling resistance is constant throughout operation speed of the vehicle, rolling resistance dominates the drag losses at low speeds and aerodynamic drag is dominant at higher speed.

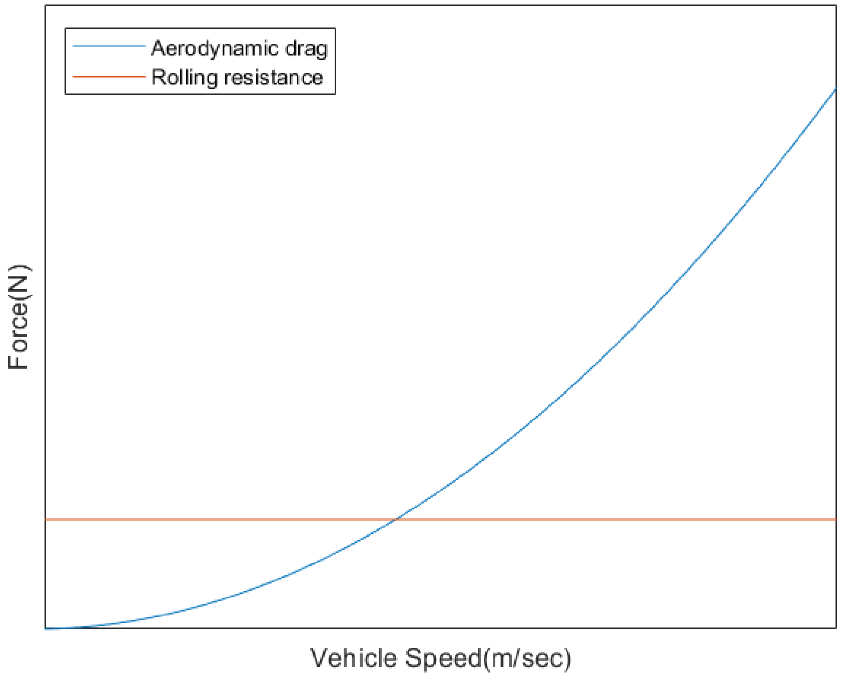


Figure 2.2: Aerodynamic drag and rolling Resistance

2.1.3 Gradient driving force

When a vehicle is moving up on an inclined road by the virtue of its weight, the vehicle experiences a resistive force because of the gravity acting on the vehicle which results in more energy consumption. When a vehicle is moving down on an inclined road this gradient driving force adds up to the net traction force resulting in less energy consumption, whereas driving on a flat road has a neutral effect on energy consumption. F_{Grad} is given by,

$$F_{\mathrm{grad}} = m_{\mathrm{veh}} g \sin \alpha \tag{2.7}$$

where m_{veh} is mass of the vehicle, g is acceleration due to gravity.

2.2 Driving cycle

"A driving cycle is a series of data points representing the speed of a vehicle versus time" [26]. They are designed to describe the workload a vehicle needs to deliver in certain conditions, they are used to assess the performance of the vehicle, fuel consumption, tailpipe emissions, electric range, and electric motor efficiency in the case of BEV. Driving cycles are used by manufacturers to optimize the powertrain. One of the main purposes of the driving cycles is to reduce the time, cost, and effort involved in testing a vehicle on the road or test tracks very early in the design phase of the vehicle, instead the testing is carried in a lab on the chassis dynamometer in a controlled environment or in a computer simulation, where a virtually representative of the road is created with series of data points of speed versus time and virtual vehicle which is representative of the real world being tested is made to follow or achieve these data points, and these points are based on the specific use case. There are numerous driving cycles being used across the world, but few of them are commonly used namely New European Driving Cycle (NEDC) and Worldwide Harmonised Light Vehicles Test Procedure(WLTP).

2.2.1 NEDC

NEDC driving cycle is theoretically based on the real world driving as a guidance, originally designed to asses fuel consumption and emission level certification of passenger vehicle.The NEDC consists of four consecutive Urban driving cycle(UDC) followed by extra urban driving cycle(EUDC), NEDC cycle is shown in Figure 2.3. The resultant drive pattern has a lower acceleration, constant speed for longer duration and many resting period which is not a good representative of present day driving scenario with steeper acceleration and less resting period, it has received criticism for larger difference in indicated and real world emission values.

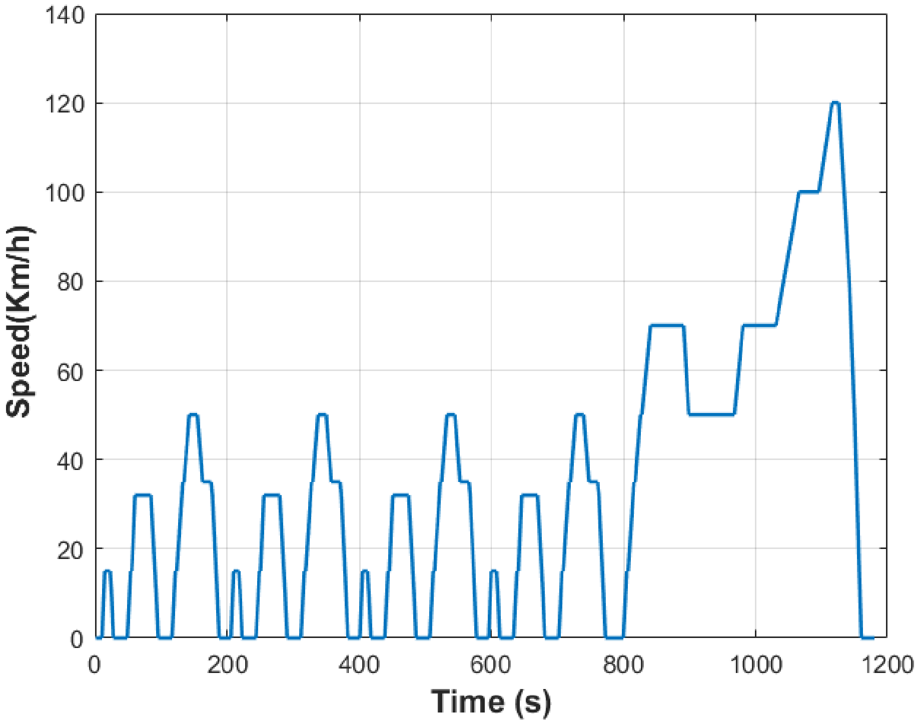


Figure 2.3: New European Driving Cycle (NEDC)

The NEDC covers a total disatnce of 10932 meters or 10.932 KM in 1220 second, with average speed of 33 km/h and maximum acceleration of 1.2 m/s^2 and a stopping duration of 305 seconds which is around 25 % of total duration. The parameters are tabulated in Table 2.1.

Parameters	Values
Distance, m	10932
Duration, Sec	1220
Stop duraction, sec	305
% of Stop	25 %
Average speed, km/h	33
Maximum acceleration, m/s^2	1.2

Table 2.1: NEDC Parameters

2.2.2 WLTP

To overcome the shortcomings of NEDC, a new driving cycle was formulated by the United Nations Economic Commission for Europe (UNECE) known as Worldwide Harmonised Light Vehicles Test Procedure(WLTP) designed to assess fuel consumption and emission level certification of passenger vehicle. The aim of WLTP driving cycle is capturing close to realistic vehicle behaviour to indicate more realistic values. To achieve this goal the driving cycle is created by recording the data(Speed versus time) from a vehicle driven on a particular route. This data is adjusted into four different driving phases namely urban, suburban, rural, and highway. As shown in the Figure 2.4 WLTP drive cycle is divied into multiple phases, these phase represent urban, suburban, rural, and highway respectively. Even though WLTP captures more realistic value of Emission and Energy consumption when compared to NEDC, the WLTP cycle fails to capture real world factors like traffic intensity, driver behaviour, different payload, auxillary loads and road condition. In this thesis work a traffic simulation tool is used to simulate vehicle routes with controlled traffic, vehicle and driver behaviour to extract drive cycle.

The WLTP covers a total disatnce of 23266 meters or 23.26 km in 1800 second, with average speed of 46.5 Km/h and maximum acceleration of 1.6 m/s^2 and a stopping duration of 235 seconds which is around 13.4 % of total duration. The parameters are tabulated in Table 2.2.

Parameters	Values
Distance, m	23266
Duration, Sec	1800
Stop duraction, Sec	235
% of Stop	13.4 %
Average speed, Km/h	46.5
Maximum acceleration, m/s2	1.66

Table 2.2: WLTP Parameters

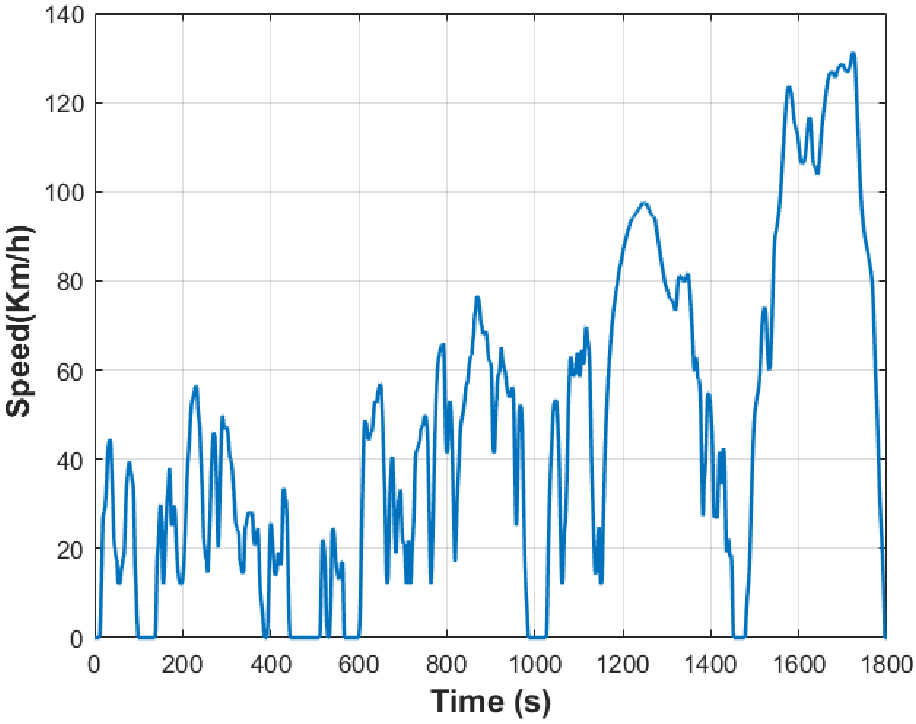


Figure 2.4: Worldwide Harmonised Light Vehicles Test Procedure(WLTP)

The standard driving cycle mentioned above fails to capture real world factors like interaction with the traffic, driver behaviour, and few other real world factors, Which affect energy consumption. A drive cycle generated with the help of traffic simulation captures the effect of the real world factors like driver behaviour and interaction with the traffic which would assist in predicting real world energy consumption. The process involved in generating a drive cycle using traffic simulation is explained in section 3.2.

2.3 BEV Powertrain

In a vehicle, the Powertrain has all the components which are responsible to convert energy/ power produced by the prime mover to the translatory motion of the vehicle. Traditional powertrain consists of engine, transmission, driveshaft, differential, and finally drive wheel and is shown in Figure 2.5. All-electric vehicle or BEV powertrain replaces internal combustion engine in the traditional powertrain with an electric drive system and electrochemical energy storage device as shown in Figure 2.6.

In a BEV Electric Motor(EM) is the main source of traction force at the wheel, the drive shaft is connected to EM through the gearbox and differential. Usually, EM is a three-phase AC type permanent magnet synchronous machine. Based on application EM is arranged in multiple configurations ranging from the rear-wheel-drive, which usually uses single EM with single driveline unit(drive shaft, gearbox, and differential), All Wheel Drive (AWD) uses dual EM and dual-driveline unit for both the EM. Energy in BEV is stored in a high voltage battery. The control system controls the amount of energy delivered to EM from the battery based on the driver input. In a vehicle EM is designed for higher speed level in order bring down the size of the EM, but wheel tend to spin out when driving at a higher speed because of the design principle of EM, to overcome this a step down gearbox is used [13]. When driving a vehicle on curved road, the inside and outside wheel tend to rotate at a different speed. Therefore a differential is used in the powertrain to overcome this issue.

Figure 2.5: Traditional Powertrain [8]

Figure 2.6: Battery Electric Powertrain [11]

2.4 Auxiliary system

Auxiliary system in an automobile represents electrical components like climate control, seat heating, light system, infotainment system, battery thermal management whose purpose range from security, comfort and safety of the system like battery and invertor cooling. In traditional vehicles electrical energy consumed by the auxillary system is compensated by driveshaft from the IC engine, but in the case of BEV, Auxillary systems are driven by stored energy in the batteries affecting the range of the vehicle.

2.5 Traffic simulation

"Traffic simulation or the simulation of transportation systems is the mathematical modeling of transportation systems (e.g., freeway junctions, arterial routes, roundabouts, downtown grid systems, etc.) through the application of computer software to better help plan, design, and operate transportation systems" [2]. Traffic simulation can be used to understand and predict vehicle of interest i.e, ego vehicle's interaction with its surrounding traffic which is the basic building block of this thesis work. Here in traffic simulation, focus is more inclined towards predicting driver behaviour more accurately than dynamics of the vehicle except for basic function like acceleration and speed of the vehicle. In traffic simulation simulated vehicle reflects every day human driving and its response to surrounding traffic, all the activities of the driver impact the traffic flow of that particular segment result in realistic traffic behaviour.

2.5.1 Traffic flow model

Traffic simulation is classified into three classes of traffic flow model: Macroscopic traffic model, Microscopic traffic model,and Mesoscopic traffic flow model [27]. "The macroscopic traffic flow model is the mathematical model considering the aggregate behavior of traffic flow i.e it is built on the assumption that whole traffic is assumed to be a fluid stream, with the flow equation representing individual vehicle as a particle of the fluid stream" [1] [16]. The macroscopic traffic flow model gives a general idea about whole traffic and its characteristic such as mean of the traffic, flow rate, density of the traffic but it fails to address the impact at a vehicle level and how it affects the traffic.

But on the other hand Microscopic traffic model captures the effect of each vehicle and its interaction with the surrounding vehicle in a large traffic network, this interaction effects the behaviour of surrounding traffic. it is based on the assumption that the vehicle behavior depends on the differential equation and the parameters which depict human behavior on the road. The Mesoscopic traffic flow model is a combination of the Microscopic and Macroscopic model, Mesoscopic traffic flow model is balance between micro and macroscopic model which is designed to describe the traffic flow for small road network with aggregate value and vehicle defined at individual level [15]. Figure 2.7 represents all the traffic model discussed.

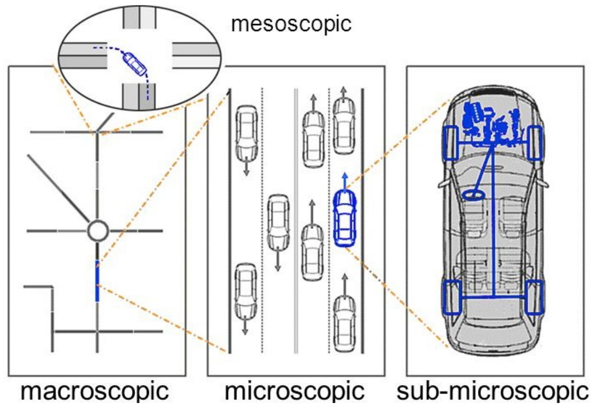


Figure 2.7: Traffic simulation model [27]

Microscopic traffic flow model is the more detailed and accurate model of all the above mentioned traffic flow model. In order to capture detailed effect of traffic scenarios and driver behaviour of an individual vehicle on a large road network, microscopic traffic simulion tool Simulation of Urban MObility (SUMO) is used in this thesis work.

2.5.2 SUMO

"SUMO is an open-source software package developed by the Institute of Transportation Systems at the German Aerospace Center with the aim of understanding and evaluating road infrastructure" [25]. SUMO comes with a large number of built-in tools to build and assess large road network it also offers flexibility in configuring vehicle parameters, traffic lights, vehicle route, road network, and flow parameters. SUMO supports intermodal simulation with heterogeneous vehicle distribution like public transport, pedestrians, cyclists, etc. SUMO offers a network editor know as netedit which is used for importing, building network, and editing the network accompanied by SUMI GUI which is used as visual interface and to run the simulation. OSM Web Wizard tool is used to import road network from OpenStreetMap, sattelite background image and public transport information.

2.5.3 Car-following model

The most important part of traffic simulation is Car-following model, as it is used to simulate the longitudinal behaviour of the vehicle when following another vehicle. Interaction between the vehicle and how they tend to maintain safe distance in order to avoid collision, Krauss and IDM are the prominent car-following model, these are discussed below.

Krauss Car Following Model: The Krauss car following model was proposed by Stefan Krauß [17], this model is collision-free and it is based on the safe speed. In the car-following model prediction of vehicle dynamics is based on the position and velocity of the leading vehicle. In this model velocity of the following vehicle is calculated based on the velocity of the leading vehicle, the gap between the vehicles in term of time step and reaction time of the driver. The calculated velocity is the safe velocity v_{safe}, this velocity is used to calculate the desired velocity v_{des}.

$$v_{\mathrm{safe}}(t) = v_{\mathrm{l}}(t) + \frac{g(t) - v_{\mathrm{l}}(t)\tau_{\mathrm{k}}}{\frac{v_{\mathrm{l}}(t)+v_{\mathrm{l-1}}(t)}{2b_{\mathrm{max}}} + \tau_{\mathrm{k}}} \tag{2.8}$$

$$v_{\mathrm{des}}(t) = min(v_{\mathrm{max}}, v_{\mathrm{l}}(t) + a_{\mathrm{max}}t, v_{\mathrm{safe}}) \tag{2.9}$$

Where $v_{\mathrm{l}}(t)$ is the Velocity of leading vehicle, b_{max} is the maximum deceleration of the vehicle, $g(t)$ is the bumper to bumper gap between the vehicles in t, τ_{k} is the reaction time of the driver usually one second. Krauss car-following model is the default model in SUMO [18].

Intelligent Driver Model: Intelligent Driver Model(IDM) is, follow the leader model proposed by Martin Treiber[28]. It is based on optimal velocity model and is collision free. The model calculates acceleration of the vehicle based on velocity of the vehicle, bumper to bumper gap between the current and leading vehicle and velocity difference to the leading vehicle.

$$a_\alpha(t) = a_{\mathrm{max}}\left[1 - \left(\frac{v_\alpha(t)}{v_{\mathrm{des}}(t)}\right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha(t)}\right)^2\right] \tag{2.10}$$

Where,

$$s^*(v_\alpha, \Delta v_\alpha) = s_0 + v_\alpha(t)T + \frac{v_\alpha(t)\Delta v_\alpha(t)}{2\sqrt{a_{max}b_{max}}} \tag{2.11}$$

$$s_\alpha(t) = x_{\alpha-1}(t) - x_\alpha(t) - l_{\alpha-1} = \Delta x(t) - l_{\alpha-1} \tag{2.12}$$

Where a_α is calculated acceleration of the vehicle, a_{max} is the maximum desired acceleration, v_α is the velocity of the current vehicle, v_{des} is desired velocity,Δv_α is the velocity difference to the leading vehicle, b_{max} is the maximum desired deceleration, s_0 is the minimum desired distance front the leading vehicle, T is the time headway, $x_{\alpha-1}$ is the position of the leading vehicle, x_α is the position of the current vehicle and $l_{\alpha-1}$ is the length of the leading vehicle.

In this thesis work, IDM implemented in SUMO is used as a car-following model, it was found from the literature survey that IDM performed better in replicating real-world driver trajectories and it better represented the real-world driver in case of traffic flow and energy consumption than Krauss car-following model [4] [5]. Table 2.3 represents the list of Vehicle type Parameters used by IDM.

Attribute	Description
minGap	Minimum gap when standing(in m)
accel	The acceleration ability of a vehicle (in m/s^2)
decel	The deceleration ability of a vehicle (in m/s^2)
emergencyDecel	The maximum deceleration ability of a vehicle of this type in case of emergency (in m/s^2)
sigma	The driver imperfection
maxSpeed	The vehicle's maximum velocity (in m/s)

Table 2.3: IDM Parameters used in SUMO [6]

2.5.4 Lane changing model

In traffic simulation Lane-changing model is equally important as car-following, as it controls the lateral behaviour of the vehicle determining the lane choice and minor speed adjustments while lane change maneuver. In real world traffic, lane change maneuver aids in gaining speed when driving behind a slow driver in multilane road and it also has significant effect on the traffic flow [19]. SUMO offers two lane changing model: LC2013(Lane-change model) [10] and SL2015(Sublane-model) [3], LC2013 is a deafult lane changing model of SUMO, it is used in this thesis work. Table 2.4 represents the list of parameters used by LC2013 lane changing model.

Attribute	Description
lcStrategic	The eagerness for performing strategic lane changing.
lcCooperative	The willingness for performing cooperative lane changing.
lcSpeedGain	The eagerness for performing lane changing to gain speed.
lcKeepRight	The eagerness for following the obligation to keep right.
lcOvertakeRight	The probability for violating rules gainst overtaking
lcOpposite	The eagerness for overtaking through the opposite-direction lane.
lcAssertive	Willingness to accept lower front and rear gaps on the target lane.
lcCooperativeSpeed	Factor for cooperative speed adjustments.

Table 2.4: LC2013 Parameters used in SUMO [6]

3

Methods

In this thesis work, the main goal was well defined from the beginning, which helped in planning the workflow more effectively. The main aim is to investigate the effect of traffic intensity and aggressiveness of the driver on the energy consumption of BEV range. Methodology involved in the process is presented in this section.

3.1 Route Selection

Route selection was the basic building block of this project. For analysis, real-world locations were used for modeling the traffic in simulation environment. CEVT has defined a route that represents real-world driving, which consists of rural, urban, and motorway road segments in and around Gothenburg city. CEVT real-world driving route is shown in Figure 3.1, because of the confidentiality of the data, only outline of the route is presented.

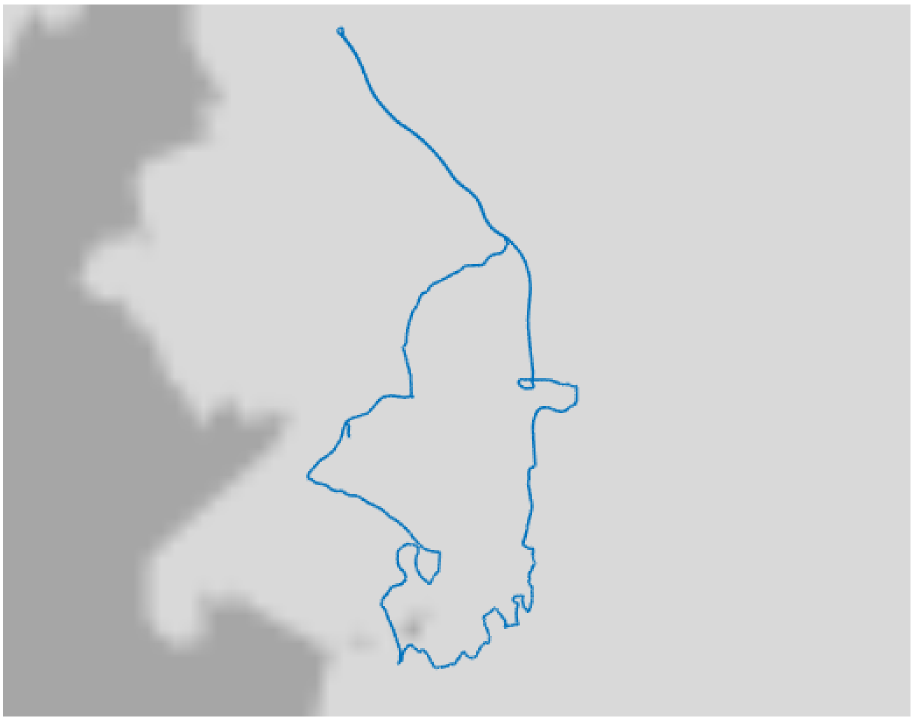


Figure 3.1: CEVT real-world driving route.

Instead of modeling all the three road segments of the real-world driving route as a single route, it was of interest to model the three road segments separately to determine the effect of each road segment mentioned above on the energy consumption of BEV. So, from the real-world driving route, three different road segments namely rural, urban, and motorway were picked for traffic simulation. The road segments were picked such that each segment is confined to itself and the intersecting portion between the two road segments was not considered i.e. rural part of the CEVT real-world driving road was selected such that the route was confined to the rural portion of the city and the transition between the rural and urban or rural and motorway was excluded.

3.1.1 Rural road segment

The rural road segment is approximately 13.2 km long which is a two lane road, one lane in each direction. The speed limit ranges from 50 to 70 km/h [21]. This stretch of the road consists of roundabout, intersection, on-ramp, pedestrian crossing, junction, bus-stop and traffic lights with separate lane for the cyclists, pedestrians. Rural road segment is shown Figure 3.2.

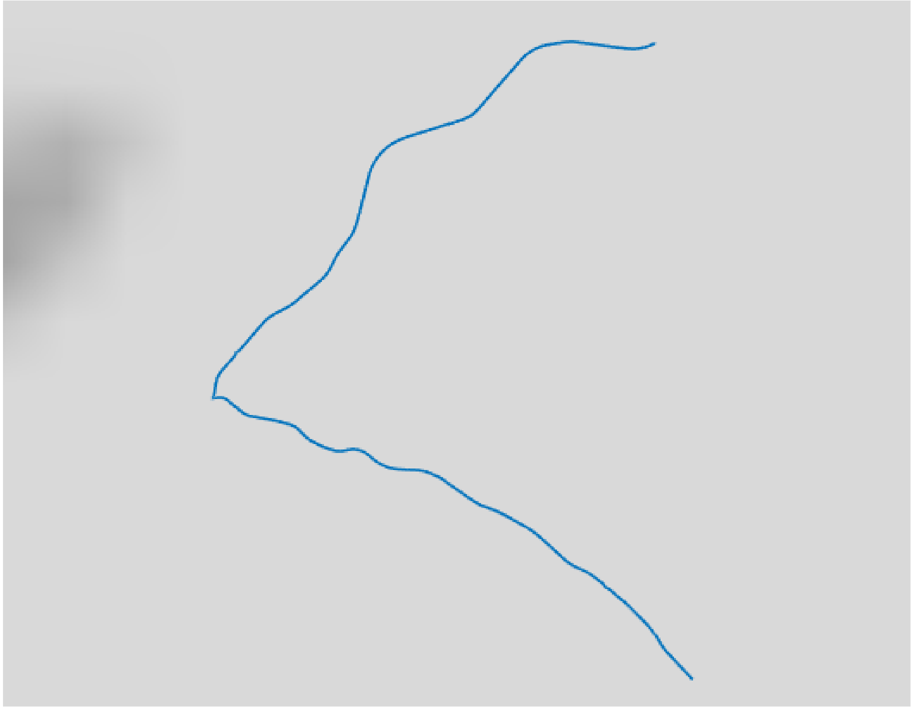


Figure 3.2: Rural road segment.

3.1.2 Urban road segment

The urban road segment is approximately 13.4 Km long, with a varying number of lanes throughout the stretch. For most of the road segment, it is a four-lane road, two lanes in each direction separated by public transport line. In some parts of the road segment, there is a two-lane road, one lane in each direction. The urban road segment has a school zone and hospital zone in its way. The speed limit ranges from 30 to 50 Km/h [21]. This stretch of the road consists of a roundabout, intersection, pedestrian crossing, junction, and traffic lights with separate lanes for the cyclist, pedestrians, and public transport throughout the stretch. Urban road segment is shown Figure 3.3.

Figure 3.3: Urban road segment.

3.1.3 Motorway road segment

The Motorway road segment is approximately 18.2 Km long, with a four-lane road, two lanes in each direction separated by a trench. The speed limit ranges from 90 to 110 Km/h [21]. This stretch of the road consists of onramp and roundabout, cyclists and pedestrians are restricted from entering this road segment. Motorway road segment is shown Figure 3.4. The speed limit of all the road segments mentioned above was obtained from Trafikverket[21] as shown in Figure 3.5.

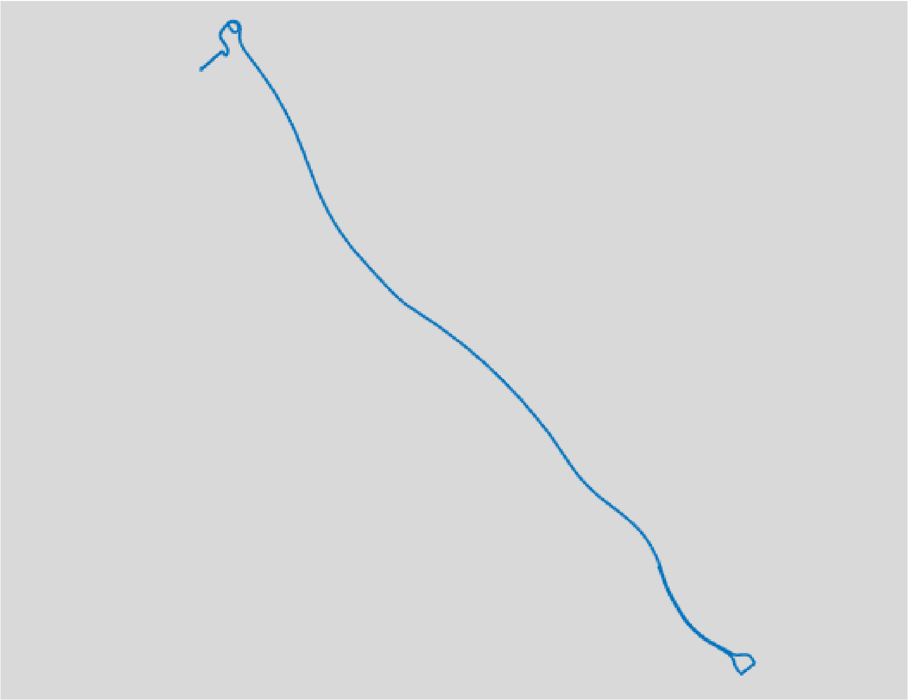


Figure 3.4: Urban road segment.

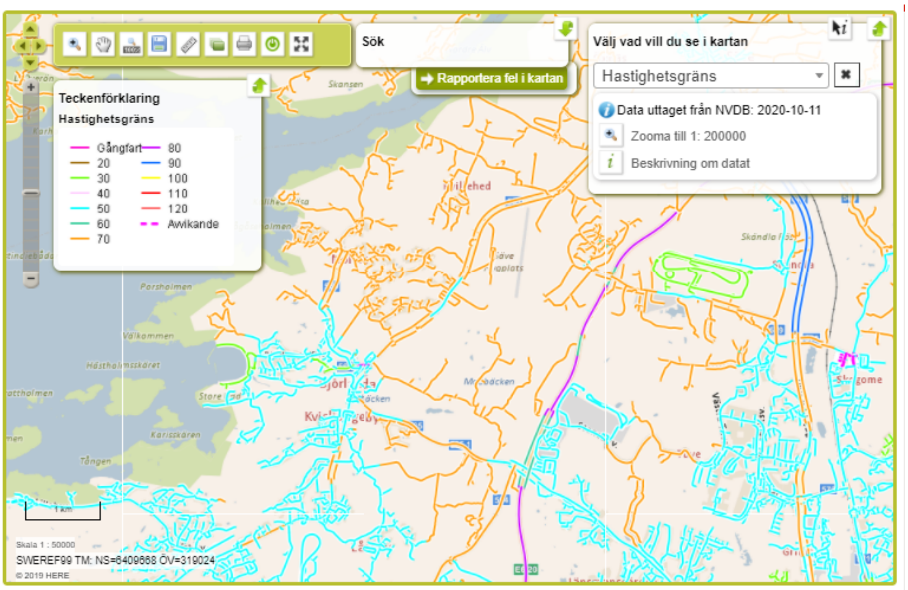


Figure 3.5: Speed limit data [21].

All the details regarding the selected road segment like roundabout, junction, pedestrian crossing etc mentioned above were initially observed in google maps. All the observations were verified during test drive on the selected road segments and these observation were considered while building and editing the road network in traffic simulation software SUMO.

3.2 Traffic simulation

As mentioned in section 2.5, SUMO is used for traffic simulation, which is capable of capturing the effect of each and every vehicle in the modelled road network accurately. Process involved in traffic simulation is presented below. Workflow for traffic simulation is shown in Figure 3.6.

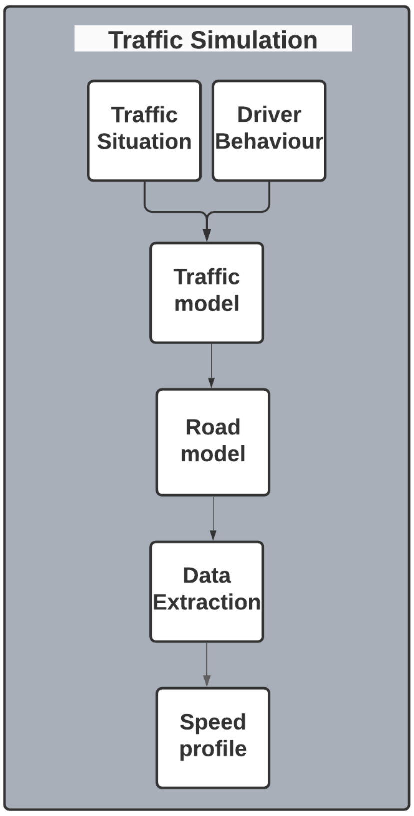
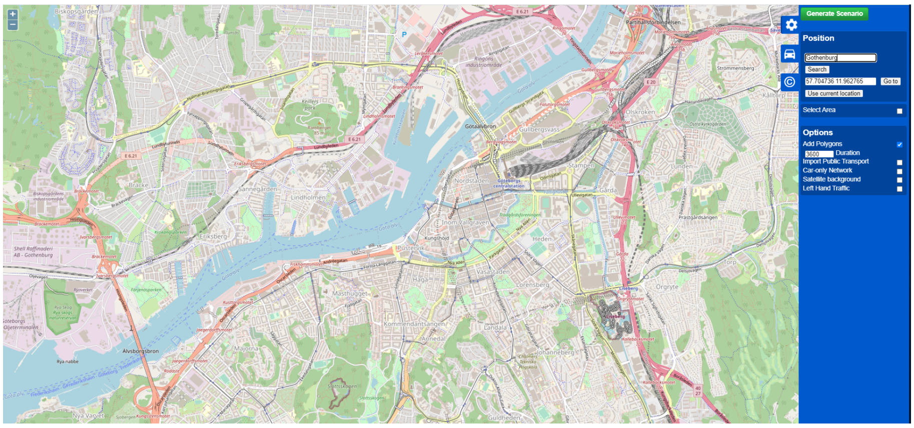


Figure 3.6: Flow chart describing work flow in traffic simulation.

3.2.1 Creating road network

SUMO allows multiple ways of importing road network to the simulation environment. One of the popular and easily accessible methods is to use OpenStreetMap (OSM) [22] along with netcovert which is a command-line application in SUMO, to create a road network in a simulation environment using OSM files. Another simple and easy method is to use OSMWebWizard [29]. SUMO offers number of tools, one among them is OSMWebWizard. "Which is a collection of python scripts with the function of importing road network from OSM file along with randomized traffic demand" [29]. In this project, OSMWebWizard is used because of its simplicity(automated network creation) and the ability to build a large road network which is not possible with the OSM method. Visual interface is shown in Figure 3.7.



Gothenburg

57.704736 11.962765

Select Area ☐

Add Polygons ☑

3600 Duration

Import Public Transport ☐

Car-only Network ☐

Satellite background ☐

Left Hand Traffic ☐

Figure 3.7: OSMWebWizard Visual interface.

As mentioned in section 3.1, three different road segments were selected. In OSMWebWizard location of the selected road segment is entered and the actual area of interest is selected using the select area option. Once the location and actual area is selected using generate scenario option, road network is generated automatically. All the embedded information regarding speed limit, traffic signal, roundabout, junction and pedestrian crossing in the OSM file is used by OSMWebWizard to create the road network. This procedure is repeated for the all the selected road segments, generated road network of rural, urban and motorway is shown in Figure 3.8, Figure 3.9 and Figure 3.10 respectively. The generated road network is further edited in netedit [20].

Figure 3.8: Rural road segment.

Figure 3.9: Urban road segment.

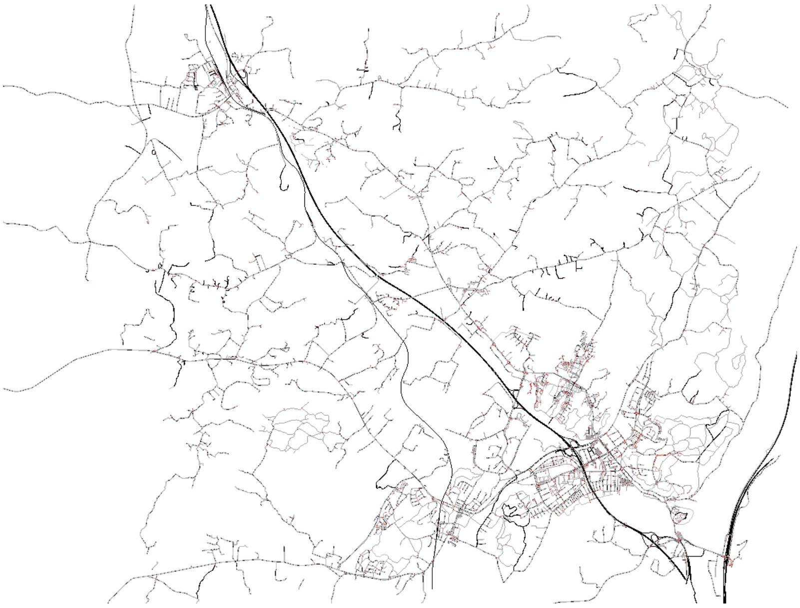
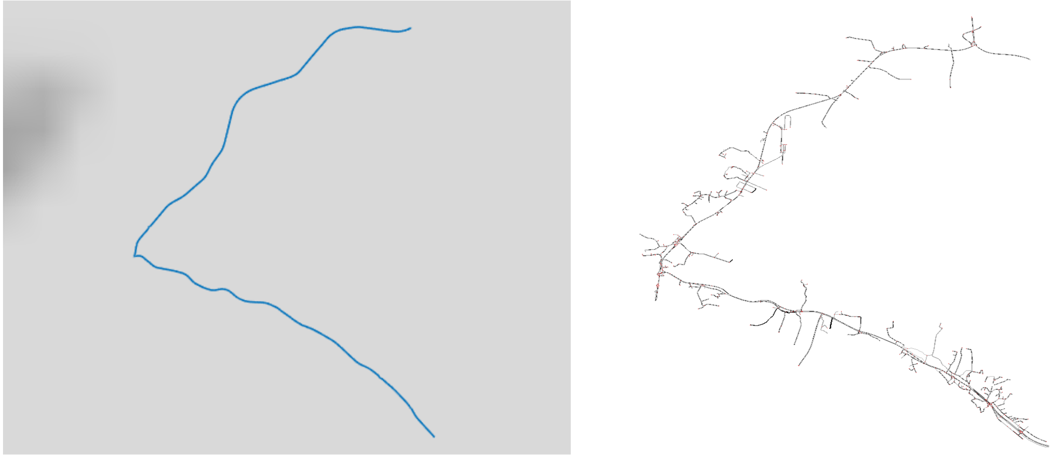


Figure 3.10: Motor road segment.

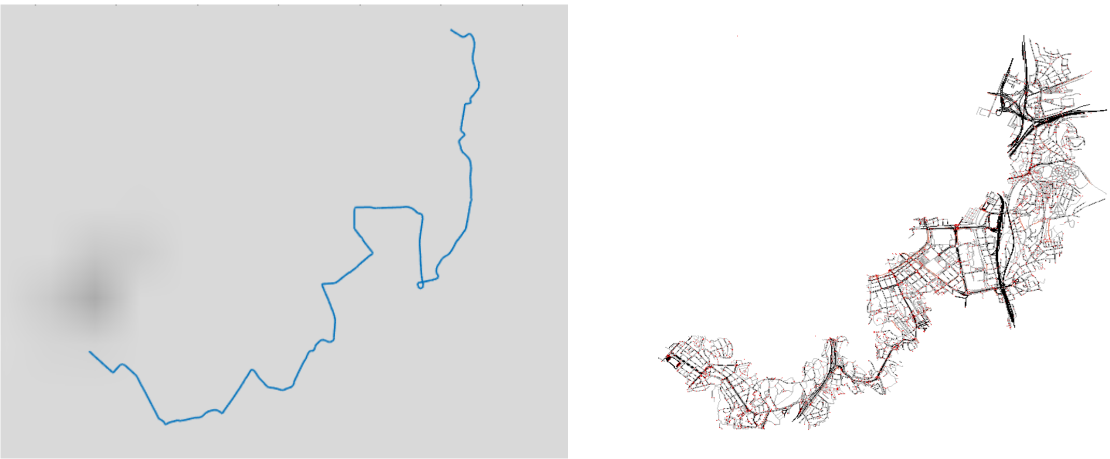
3.2.2 Editing road network

One of the most important factor is the optimum use of the computation power for a faster simulation. To achieve this, the generated road network was optimized such that the route followed by the ego vehicle is preserved. The rest of the road network which does not affect the route followed by the ego vehicle was not modeled thereby enhancing the computation speed. To have a realistic car flow into the route, entrance road, and exit road which affects the inflow of the vehicle was modeled. Comparison between selected road segment from CEVT real world driving route and modelled road network in SUMO of rural, urban and motorway is shown in Figure 3.11, Figure 3.12 and Figure 3.13 respectively.



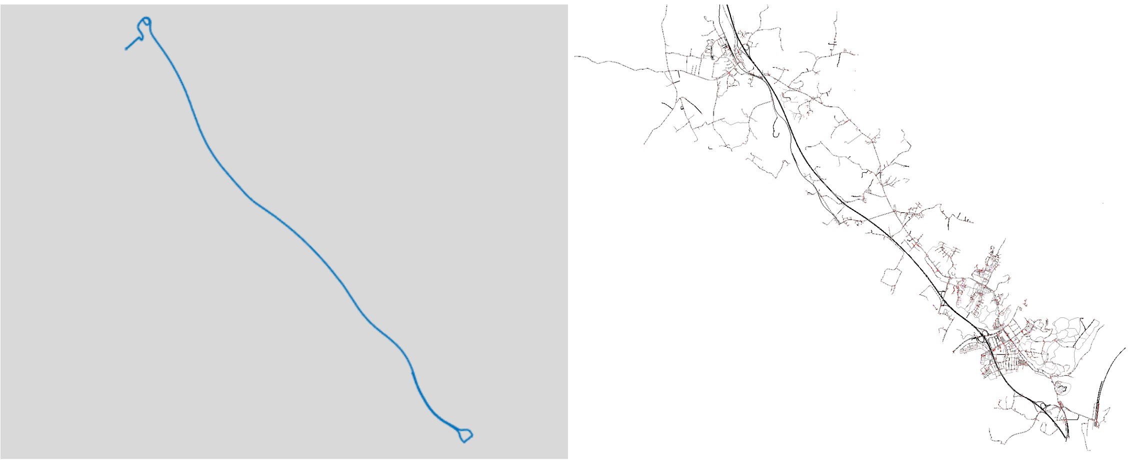
(a) Selected Rural road segment. **(b)** Modelled Rural road segment.

Figure 3.11: Comparison between selected and modelled rural road network.



(a) Selected Urban road segment. **(b)** Modelled Urban road segment.

Figure 3.12: Comparison between selected and modelled Urban road network.



(a) Selected Motorway road segment. **(b)** Modelled Motorway road segment.

Figure 3.13: Comparison Between selected and modeled Motorway road network

It can be seen from the comparison in Figures 3.11, 3.12 and 3.13 that the route selected by the ego vehicle, entrance, and exit was preserved. Rest of the nodes,junctions and edges which doesn't effect the selected route were deleted from the generated road network. Reduction in number of junctions and edges before and after optimization in Rural, Urban and Motorway is shown in Tables 3.1, 3.2 and 3.3 respectively.

Parameters	Before optimization	After optimization
Junction	4933	638
Edges	10115	1320

Table 3.1: Before and after optimization of Rural road network.

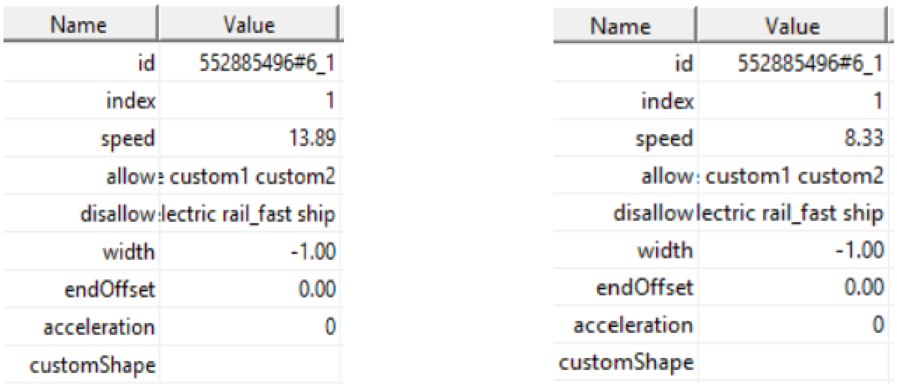
Parameters	Before optimization	After optimization
Junction	23040	7019
Edges	47142	13652

Table 3.2: Before and after optimization of Urban road network.

Parameters	Before optimization	After optimization
Junction	5174	3178
Edges	10662	6325

Table 3.3: Before and after optimization of Motorway road network.

Once the road network was built and optimized, the next detail was to implement the speed limits for all the road segements built, As mentioned above speed limit data is embedded in the osm files which is used to build the road network. Hence, speed limits were implemented along with road network, but these values were verified from the data obtained from TRAFIKVERKET [21]. It was found that for most part of the road network the speed limits were accurate except for the school zone in urban road segment which was updated to the school zone limits. Figure 3.14 shows speed limit in school zone, in SUMO by default speed limit is in m/s. Before updating it was 50 Km/h (13.89 m/s) and it was updated to 30 Km/h(8.33 m/s).



Name	Value
id	552885496#6_1
index	1
speed	13.89
allow	custom1 custom2
disallow	lectric rail_fast ship
width	-1.00
endOffset	0.00
acceleration	0
customShape	

(a) Before updating

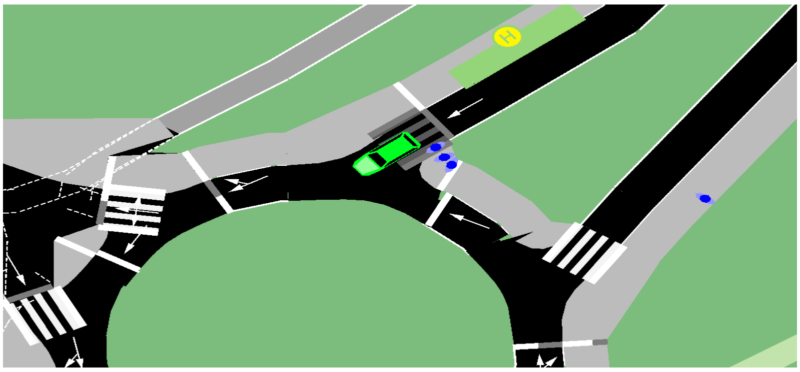
Name	Value
id	552885496#6_1
index	1
speed	8.33
allow	custom1 custom2
disallow	lectric rail_fast ship
width	-1.00
endOffset	0.00
acceleration	0
customShape	

(b) After updating

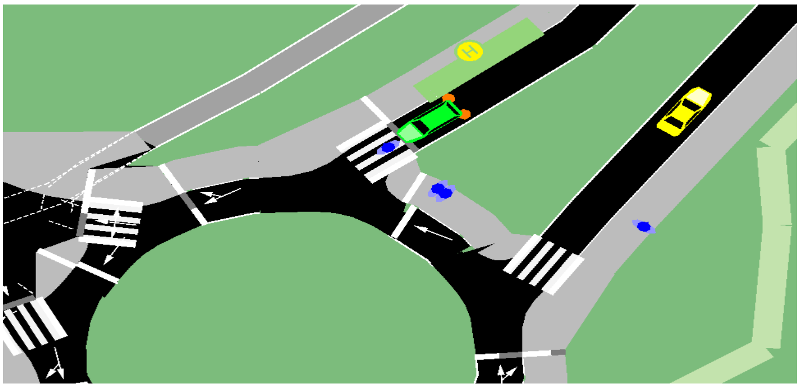
Figure 3.14: Speed limit in school zone.

During the test drive, it was observed that there were no traffic lights in the selected motorway road segment. In case of rural and urban road segment there were traffic lights and most of the traffic lights were actuated traffic lights. But, in the road network built in SUMO, it was observed that the traffic lights were static. Hence, all the traffic lights in road network were replaced by actuated traffic lights.

Pedestrians were not prioritized over vehicles in pedestrian crossing in rural road segment built in SUMO, which is not the case in real world rural road segment, they were replaced with pedestrian prioritized crossing. In urban road segment, the road network built in SUMO and real world prioritized pedestrians over vehicles, this aligns with the observations from real world road segment. It can be seen from Figure 3.15a that it is a vehicle prioritized crossing where pedestrians wait till the vehicle moves past the crossing where as Figure 3.15b shows pedestrians prioritized crossing. Here the vehicles wait till the pedestrians move past the crossing. This is the case of real world pedestrian crossing.



(a) Vehicle prioritized crossing.



(b) Pedestrain prioritized crossing.

Figure 3.15: Comparison between Pedestrain crossing

The rural road segment is a two lanes road with one lane in each direction. Bus stop and public transport are an intrinsic part of the road segment, there is no specific bus lane in this road segment. It has a direct impact on the behavior of the surrounding traffic and an indirect impact on Ego vehicle. From google maps, the exact location of the bus stops was found. The bus stops were manually added to the road segment in netedit. Figure 3.16 shows the bus stops in rural road segment, here but stop is represented by "H" symbol in road segment .By default lanes in rural road segment in SUMO are different entities and don't allow vehicles to enter into oncoming lane which is important for overtaking. So a function called "neigh" [24] was added to the modelled rural road segment which facilitated opposite lane overtaking.

In the urban road segment for most of the road network, they were separate lane for public transport, and there were very few instances like trams passing through roundabout had an impact on the traffic around it. This observation was taken into consideration, public transport was not modeled in the rest of the road network except for the section where the interaction between public transport and fleet of vehicles was observed, Figure 3.17 shows interaction between tram and traffic in one of the roundabout in urban road segment . In motorway public transport was part of the fleet vehicle and it was modeled the same. Since bus stops didn't have any interaction with the traffic because of the separate lane for public transport, they were not modeled in both the Urban and motorway road segment.

In all the road segment roundabout, intersection were manually edited in netedit according to observation made in google maps.

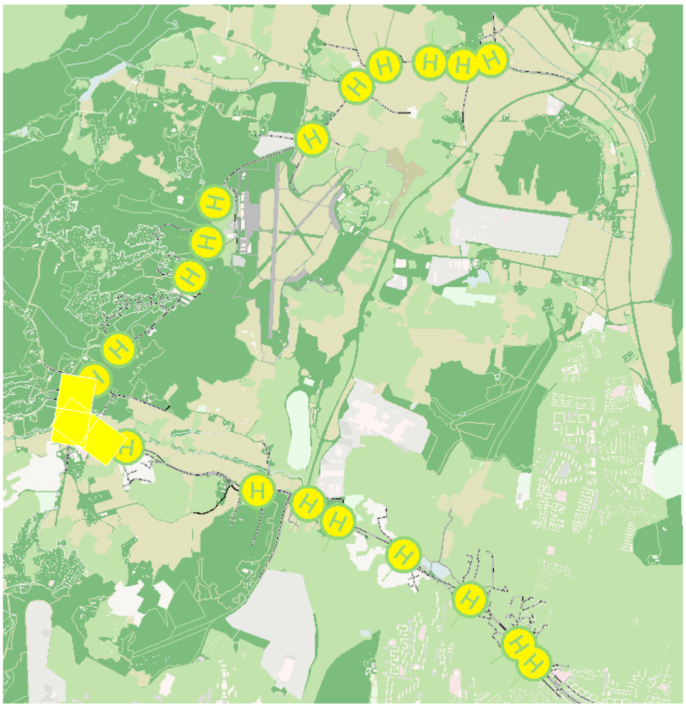


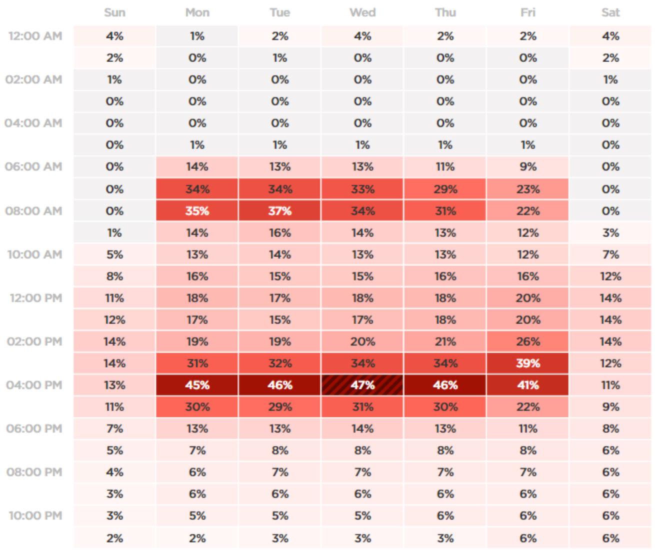
Figure 3.16: Bus stops in rural road segemt

(a) real world Round from google maps **(b)** Modelled round about in SUMO

Figure 3.17: Comparison Between real world and modelled Roundabout

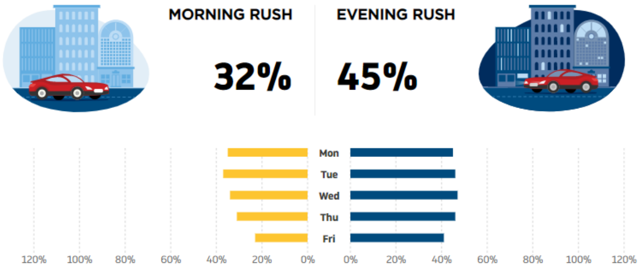
3.2.3 Traffic data Collection

In traffic simulation it is important to regulate number of vehicle on the road to capture realistic traffic behaviour. Data regarding the traffic flow was given great importance. From the commencement of the thesis one of the objective was to carry out the traffic simulation to capture the effect of traffic on Ego vehicle in the rush hours and low traffic hours in a day. It was found from the historical data that on an average congestion in Gothenburg was more in the evening than in the morning, moderately less traffic congestion in the afternoon [12]. It can be seen from Figure 3.18b congestion on an average is more in the evening than in the morning on every day of the week. So, afternoon between 12:00 to 13:00 and evening between 16:00 to 17:00 were considered for simulation.



	Sun	Mon	Tue	Wed	Thu	Fri	Sat
12:00 AM	4%	1%	2%	4%	2%	2%	4%
	2%	0%	1%	0%	0%	0%	2%
02:00 AM	1%	0%	0%	0%	0%	0%	1%
	0%	0%	0%	0%	0%	0%	0%
04:00 AM	0%	0%	0%	0%	0%	0%	0%
	0%	1%	1%	1%	1%	1%	0%
06:00 AM	0%	14%	13%	13%	11%	9%	0%
	0%	34%	34%	33%	29%	23%	0%
08:00 AM	0%	35%	37%	34%	31%	22%	0%
	1%	14%	16%	14%	13%	12%	3%
10:00 AM	5%	13%	14%	13%	13%	12%	7%
	8%	16%	15%	15%	16%	16%	12%
12:00 PM	11%	18%	17%	18%	18%	20%	14%
	12%	17%	15%	17%	18%	20%	14%
02:00 PM	14%	19%	19%	20%	21%	26%	14%
	14%	31%	32%	34%	34%	39%	12%
04:00 PM	13%	45%	46%	47%	46%	41%	11%
	11%	30%	29%	31%	30%	22%	9%
06:00 PM	7%	13%	13%	14%	13%	11%	8%
	5%	7%	8%	8%	8%	8%	6%
08:00 PM	4%	6%	7%	7%	7%	7%	6%
	3%	6%	6%	6%	6%	6%	6%
10:00 PM	3%	5%	5%	5%	6%	6%	6%
	2%	2%	3%	3%	3%	6%	6%

(a) Traffic Congestion in a day



(b) Rush hours in a day

Figure 3.18: Rush hours traffic congestion in Gothenburg [12]

Once the rush and low traffic hours were decided, traffic flow data during these hours was obtained from TRAFIKVERKET [30]. In motorway and rural road segment traffic flow data for every hour for most of the roads were obtained from sampling points. Figure 3.19 Shows sampling points spread out in Gothenburg. In case of urban road segment, there were not enough sampling points throughout the road segment found. Instead average traffic flow over the area was obtained as shown in

Figure 3.20. From congestion table based on historical data as shown in Figure 3.18a and traffic flow data from sampling points in rural and urban road segments it was found that traffic in low traffic hours was almost half of that in rush hours. Therefore, it was assumed that in urban road segment the average traffic flow obtained is the traffic flow during rush hours and half of that number was traffic flow during low traffic hours.

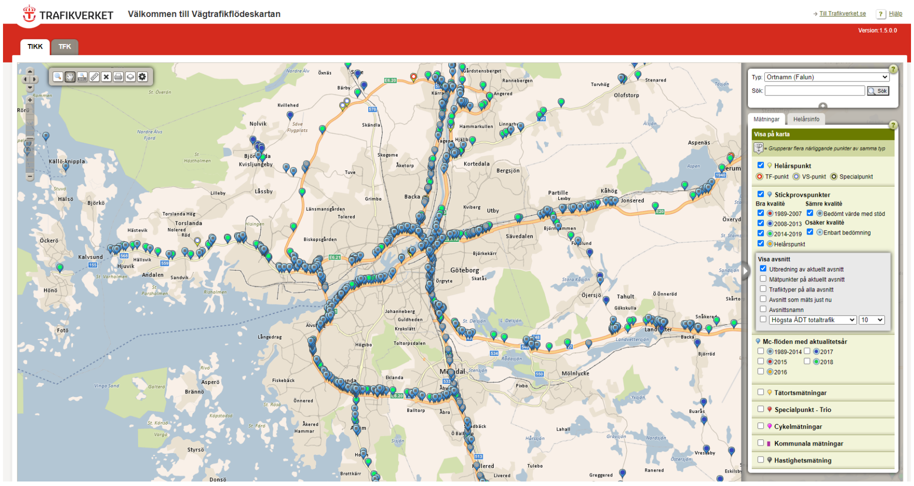


Figure 3.19: Sampling points spread out in Gothenburg [30]

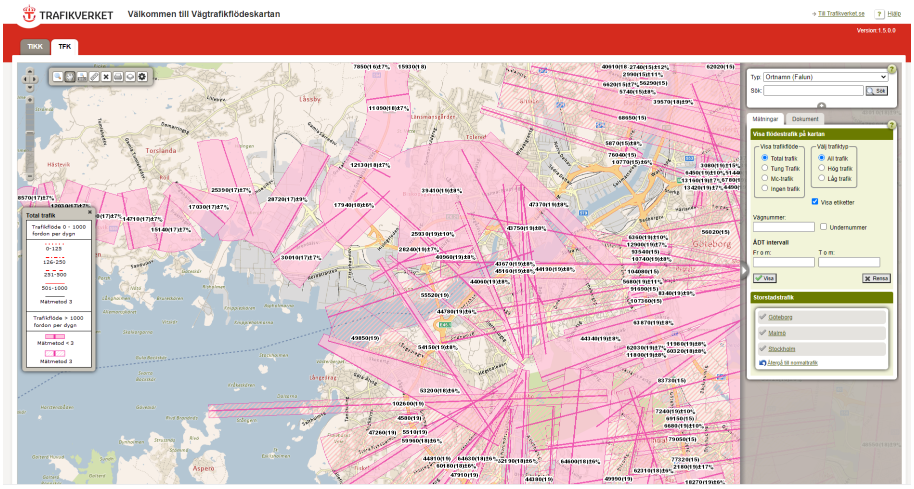


Figure 3.20: Traffic flow data in Gothenburg [30]

3.2.4 Traffic demand generation

In SUMO, based on the type of data available there are multiple ways to generate traffic demand namely trip definitions, flow definitions, Using flow definitions and turning ratios, OD-matrices, etc [7]. Since we have traffic flow information, the flow definitions method is used for demand generation. Flow definitions method is implemented in Netedit. To generate demand using the flow definitions method, the first step is to create a route in the built road network using route mode. Once the route mode is selected, the route is created by selecting the first lane, last lane, and the lanes which the Ego vehicle will follow as per the selected real world driving route for each of the road segment.

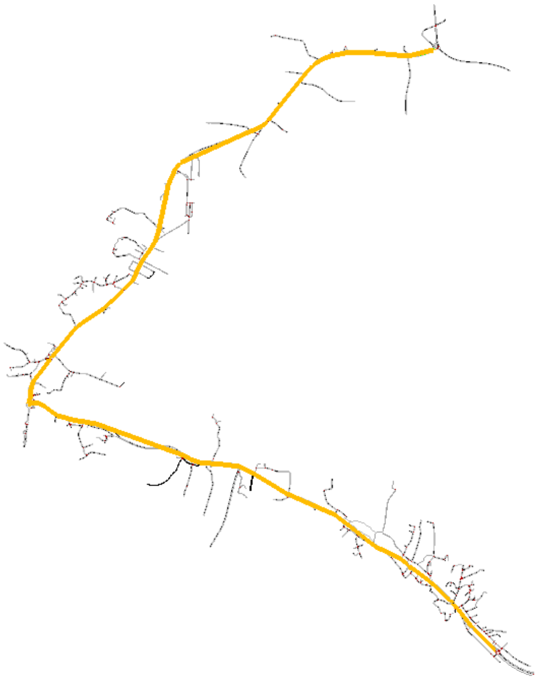


Figure 3.21: Route created in rural road segment

In Figure 3.21 orange line on the road network shows route created for Ego vehicle to follow. The same procedure is followed to create route for Ego vehicle on both urban and motorway road segments. The next step is to create a vehicle type based on the vehicle distribution data, the distribution is based on the observation made during the test drive. "Vehicle type describes the physical parameters like vehicle class, length, maximum velocity, acceleration & deceleration, car-following model"[6]. The parameters of ego vehicle are set manually except for physical parameters but for the rest of the traffic, default parameters for each of specific vehicle type is selected. These default values are shown in [31].

Demand is being generated using the route, vehicle type, and flow data defined above. This is done using the flow trip option in vehicle mode, whose input is route, vehicle type, and traffic flow in vehicles per hour. The traffic in the main route was maintained constant by regulating the traffic on the entrance and exit road to preserve the interaction at junctions and intersection to replicate real world traffic behavior. Figure 3.22 shows the demand generated using flow trips which consists of vehicle type distribution and flow instructions.

In real world traffic, desired driving speed varies among the vehicle fleet, but traffic generated using flow trip method and vehicle type results in a fleet of vehicle with homogeneous speed where no vehicle in the fleet will catch up with the leader vehicle and this is not a realistic traffic behaviour. To avoid this, normal distribution for vehicle speed is defined which clubs the effect of speed factor and speed deviation. In real world traffic, drivers don't follow or drive at speed limits and tend to drive slightly above or below the speed based on the road conditions. This can be modelled using "speed factor parameter which is usually multiplied with the speed limit to determine the desired driving speed" [6]. SpeedDev is a parameter which is a result of deviation of driver's desired speed from speedFactor. normal distribution for vehicle speed is given as "speedFactor= normc(1,0.1,0.1,1)" which result in in fleet of vehicles with 95% of the vehicle drive between 90% and 110% of the speed limit with a small deviation of 0.1. The traffic flow in the road segment is monitored using detectors which is a yellow colored sensor as shown in Figure 3.23.

```
<routes>

<vType id="Bus" length="11.50" minGap="2.40" maxSpeed="37.50" speedFactor="normc(1.00,0.10,0.1
<vType id="Delivery" minGap="2.40" maxSpeed="75.00" speedFactor="normc(1.00,0.10,0.20,2.00)" v
<vType id="Sedan" length="4.70" minGap="2.40" maxSpeed="75.00" speedFactor="normc(1.00,0.20,0.
<vType id="Truck" length="11.50" minGap="2.40" maxSpeed="36.00" speedFactor="normc(1.00,0.10,0
<vType id="hatchback" length="4.30" minGap="2.40" maxSpeed="75.00" speedFactor="normc(1.00,0.2
<vType id="wagon" length="4.80" minGap="2.40" maxSpeed="75.00" speedFactor="normc(1.00,0.10,0.

<flow id="sec1_truck1" type="Truck" begin="0.00" from="41291147#0" to="13865744#1"  via="13865
end="3600.00" vehsPerHour="260.00"/>
<flow id="sec1_bus1" type="Bus" begin="0.00" from="41291147#0" to="13865744#1" end="3600.00"
via="13865744#1" vehsPerHour="150.00"/>
<flow id="sec1_hatch1" type="hatchback" begin="0.00" from="41291147#0" to="13865744#1"
via="13865744#1" end="3600.00" vehsPerHour="100.00"/>
<flow id="sec1_sedan1" type="Sedan" begin="0.00" color="227,227,227" from="41291147#0"
to="41291147#0" via="13865744#1" end="3600.00" vehsPerHour="130.00"/>
<flow id="sec1_wagon1" type="wagon" begin="0.00" departLane="best" color="197,29,49" from="412
to="13865744#1" via="13865744#1" end="3600.00" vehsPerHour="100.00"/>
<flow id="sec2_hatch1" type="hatchback" begin="0.00" from="41291147#0" to="134270724"
via="183185024 180082646#0 13865739#0" end="3600.00" vehsPerHour="18.00"/>
<flow id="sec2_sedan1" type="Sedan" begin="0.00" color="227,227,227" from="41291147#0"
to="286505028#2" via="13865740 237772657" end="3600.00" vehsPerHour="98.00"/>
<flow id="sec2_truck1" type="Truck" begin="0.00" from="41291147#0" to="13865738"
via="180082646#0" end="3600.00" vehsPerHour="3.00"/>
<flow id="sec2_wagon1" type="wagon" begin="0.00" color="197,29,49"  from="41291147#0"
```

Figure 3.22: Demand generated file

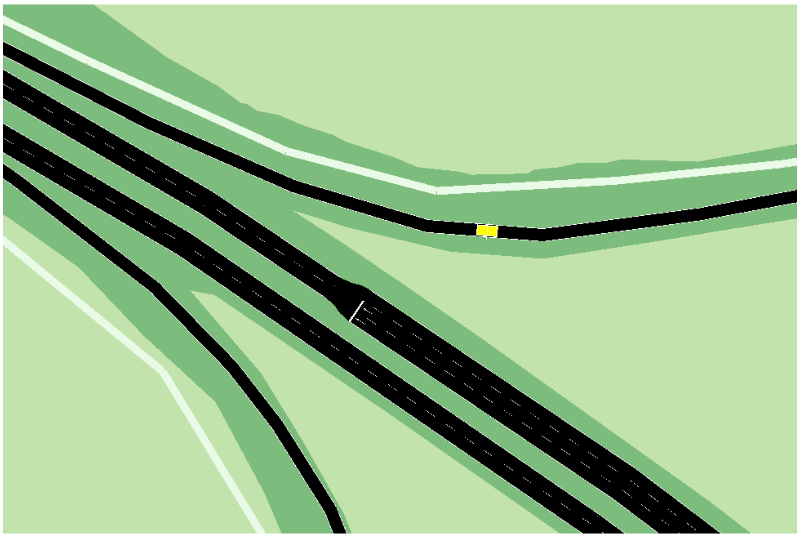


Figure 3.23: Detector in the road network

3.2.5 Driver behaviour

In addition to traffic, it was also of interest to investigate the effect of driver behaviour on energy consumption of BEV. it was found from [9], that acceleration can be used to define the driver behaviour. Based on this, the driver was categorised into three types namely defensive, normal and aggressive driver. Other parameters like distance to next vehicle, impatient driver, experienced and inexperienced driver defines the driver behaviour but this thesis was confined to driver aggressiveness. Parameters chosen for different drivers are shown in Table 3.4. As mentioned in subsection 3.2.4 parameters for Ego vehicle are manually set, which is based on driver behaviour and varied according to the case setup.

Driver type	**Acceleration**	**Deceleration**
Defensive	1.5	-1.5
Normal	2.5	-3.5
Aggressive	3.5	-4.5

Table 3.4: Parameters for different driver behaviour.

3.2.6 Data Processing

Once the traffic flow information, driver behavior, and the route are set up, the simulation is run and visualized using SUMO GUI. SUMO allows multiple methods to generate vehicle information like raw vehicles position dump, emissions output, full output, VTK (Visualization Toolkit) output, and FCD (floating car data) output each having its own purpose. In this thesis, FCD export is used since it contains speed, position, and other parameters of all the vehicles entered in simulation at every time step and the generated output file is shown in Figure 3.25. The size of the FCD output file is large and contains information of all the vehicles in the simulation. This information can be confined to one specific vehicle in our case Ego vehicle by using 'vehicle type probe' function along with FCD export, and the generated output file is shown in Figure 3.26. From this file, the drive cycle is extracted using a python script. Work flow for data extraction is shown in Figure 3.24.

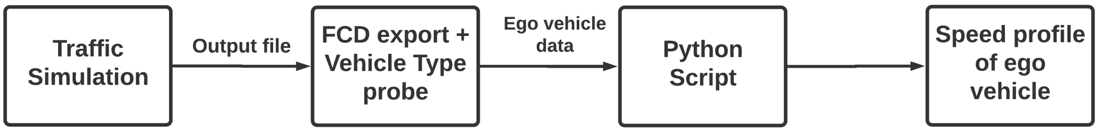
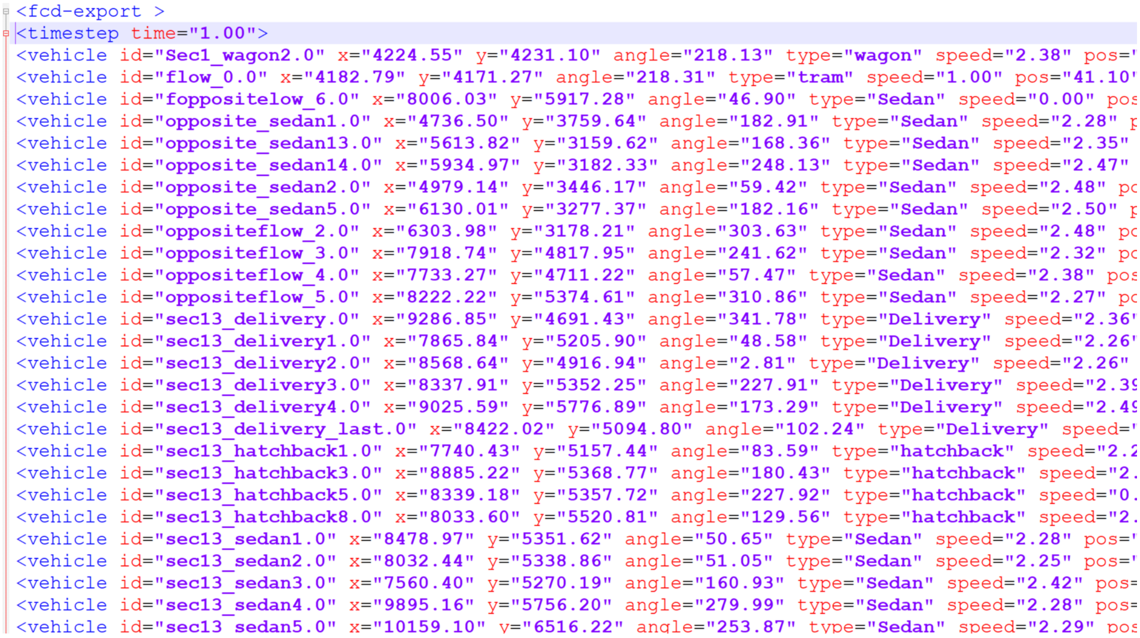


Figure 3.24: Data extration work flow



```
<fcd-export >
<timestep time="1.00">
<vehicle id="Sec1_wagon2.0" x="4224.55" y="4231.10" angle="218.13" type="wagon" speed="2.38" pos="
<vehicle id="flow_0.0" x="4182.79" y="4171.27" angle="218.31" type="tram" speed="1.00" pos="41.10"
<vehicle id="foppositelow_6.0" x="8006.03" y="5917.28" angle="46.90" type="Sedan" speed="0.00" pos
<vehicle id="opposite_sedan1.0" x="4736.50" y="3759.64" angle="182.91" type="Sedan" speed="2.28" p
<vehicle id="opposite_sedan13.0" x="5613.82" y="3159.62" angle="168.36" type="Sedan" speed="2.35"
<vehicle id="opposite_sedan14.0" x="5934.97" y="3182.33" angle="248.13" type="Sedan" speed="2.47"
<vehicle id="opposite_sedan2.0" x="4979.14" y="3446.17" angle="59.42" type="Sedan" speed="2.48" po
<vehicle id="opposite_sedan5.0" x="6130.01" y="3277.37" angle="182.16" type="Sedan" speed="2.50" p
<vehicle id="oppositeflow_2.0" x="6303.98" y="3178.21" angle="303.63" type="Sedan" speed="2.48" po
<vehicle id="oppositeflow_3.0" x="7918.74" y="4817.95" angle="241.62" type="Sedan" speed="2.32" po
<vehicle id="oppositeflow_4.0" x="7733.27" y="4711.22" angle="57.47" type="Sedan" speed="2.38" pos
<vehicle id="oppositeflow_5.0" x="8222.22" y="5374.61" angle="310.86" type="Sedan" speed="2.27" po
<vehicle id="sec13_delivery.0" x="9286.85" y="4691.43" angle="341.78" type="Delivery" speed="2.36"
<vehicle id="sec13_delivery1.0" x="7865.84" y="5205.90" angle="48.58" type="Delivery" speed="2.26"
<vehicle id="sec13_delivery2.0" x="8568.64" y="4916.94" angle="2.81" type="Delivery" speed="2.26"
<vehicle id="sec13_delivery3.0" x="8337.91" y="5352.25" angle="227.91" type="Delivery" speed="2.3
<vehicle id="sec13_delivery4.0" x="9025.59" y="5776.89" angle="173.29" type="Delivery" speed="2.4
<vehicle id="sec13_delivery_last.0" x="8422.02" y="5094.80" angle="102.24" type="Delivery" speed="
<vehicle id="sec13_hatchback1.0" x="7740.43" y="5157.44" angle="83.59" type="hatchback" speed="2.
<vehicle id="sec13_hatchback3.0" x="8885.22" y="5368.77" angle="180.43" type="hatchback" speed="2.
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Figure 3.25: FCD output file

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```

Figure 3.26: Vehicle type probe output file

3.3 Vehicle simulation

The vehicle simulation was carried out in CarMaker. Where finished vehicle model consisted of a detailed model of transmission, suspension, brakes, auxiliary systems, battery, and electric motor. These models were imported into CarMaker with the help of in house tool Automaker. The vehicle model is a BEV with regenerative brakes, operated at an ambient temperature of 23 degrees Celsius, initial SOC (State

Of Charge) of the battery was set at 80%. The friction from the road surface and auxiliary load was assumed to be constant. As mentioned in section 1.4 speed profile obtained from traffic simulation is fed as input to the vehicle model and vehicle simulation is carried out which generates output. Each driving cycle was run once for each case.

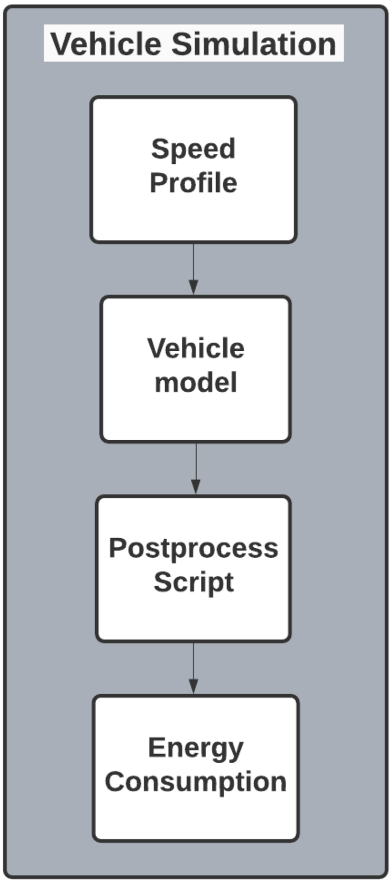

Figure 3.27: Flow chart describing work flow in vehicle simulation.

The generated output is further post-processed with the help of python script to obtain Energy consumption for each simulation. Work flow for vehicle simulation is shown in Figure 3.27. In vehicle simulation two parameters were taken into consideration that is, mass of the vehicle and load from the auxiliary system.

3.4 Case setup

In section 3.3, it is mentioned that Automaker was used to import complete vehicle model into CarMaker, and it was also used to run simulation according to the case setup which is composed of different parameters. The parameter considered are traffic condition, driver behaviour, mass, and auxiliary load. Case setup is created using matrix of parameters mentioned above with the purpose to see the impact of these parameters on Energy consumption of BEV. Case setup was built around the concept mentioned in Figure 3.28 where traffic condition and auxiliary load were grouped under mass 1 and mass 2, these mass condition were grouped under driver behaviour. Case setup for normal driver behaviour is show in Table 3.5.

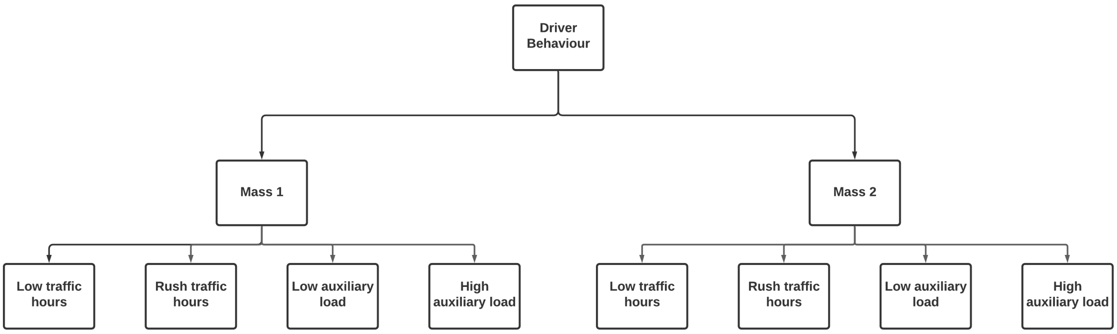

Figure 3.28: Tree structure describing case setup.

Case number	**Driver style**	**Mass**	**Auxiliary load**	**Traffic cognition**
Case 1	Normal	1500	Low load	Low traffic hours
Case 2	Normal	1500	Low load	Rush hours
Case 3	Normal	1500	High load	Low traffic hours
Case 4	Normal	1500	High load	Rush hours
Case 5	Normal	2500	Low load	Low traffic hours
Case 6	Normal	2500	Low load	Rush hours
Case 7	Normal	2500	High load	Low traffic hours
Case 8	Normal	2500	High load	Rush hours

Table 3.5: Case setup for normal driver behaviour.

We can see that there are 8 different cases for normal driver behaviour, this is repeated for other two driver behaviour type namely defensive and aggressive. A total of 24 cases for each road segment were created, Complete case setup is shown in Table A.1 which is repeated for all the road segments. The effect of the parameter mentioned above on energy consumption of BEV is presented in the next section.

4

Results and Discussion

In this section, result of the traffic and vehicle simulation performed according to the case setup mentioned in section 3.4 and the effect of driver behaviour and traffic situation on energy consumption of BEV is presented.

4.1 Drive cycle

As mentioned in section 3.2 traffic simulation was performed for different driver behaviour and traffic conditions, according to the case set up mentioned in section 3.4. Post processing of the output file from traffic simulation was performed to extract the driving cycle. As per case setup for each road segment, six driving cycle were extracted from the output file. Speed profile, acceleration profile and parameters related to each of the driving cycle is shown in AppendixA.1.

4.2 Energy Consumption

Going forward, from the case setup the effect of parameters were determined such that, for two given case all the parameters remained unchanged except for the parameter of interest. Comparing these two case would determine the impact of that particular parameter on energy consumption. Based on the case setup simulation in CarMaker was setup. The input for the simulation is driving cycle obtained from traffic simulation and other parameters discussed in section 3.4.

The output of the simulation was post processed to determine the energy consumption of BEV model. Before vehicle simulation was carried out, Carmaker driver was adapted to one of the driving cycle obtained from traffic simulation. This was done for IPG driver to follow the rest of the drive cycle from traffic simulation. Energy consumption for all the cases in rural, motorway, and urban road segment is shown in the Figure 4.1, 4.2, and 4.3 respectively. In this work the energy consumption results are in Wh/km, because of the confidentiality of the data, the plots have been normalised. From the Figure 4.1, 4.2, and 4.3 it is hard to determine any trend of energy consumption based on the case setup. So, the data obtained from the simulation was broken down and arranged to understand the impact of parameters on energy consumption in different road segment and the same is discussed in below sections.

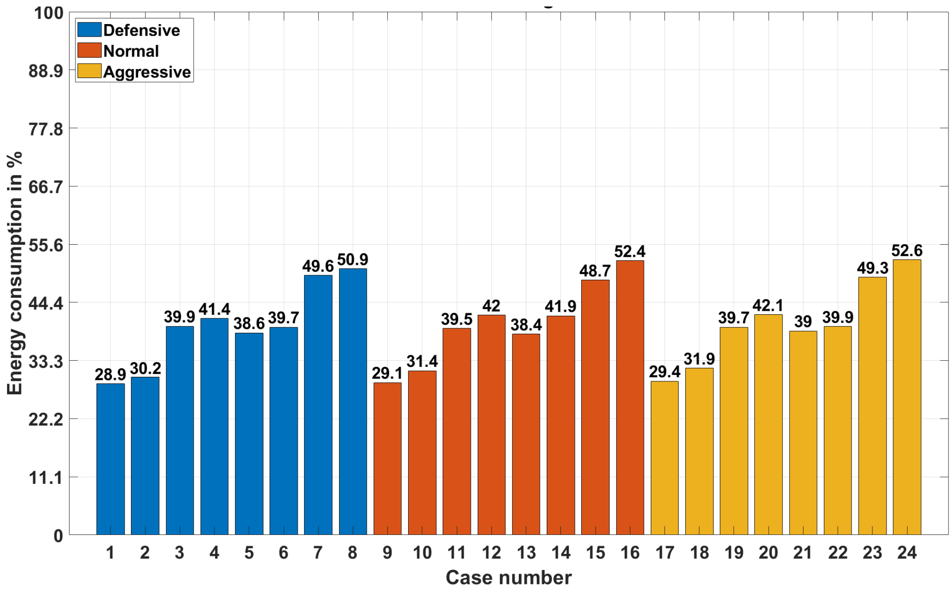

Figure 4.1: Energy consumption in rural road segment (Normalised)

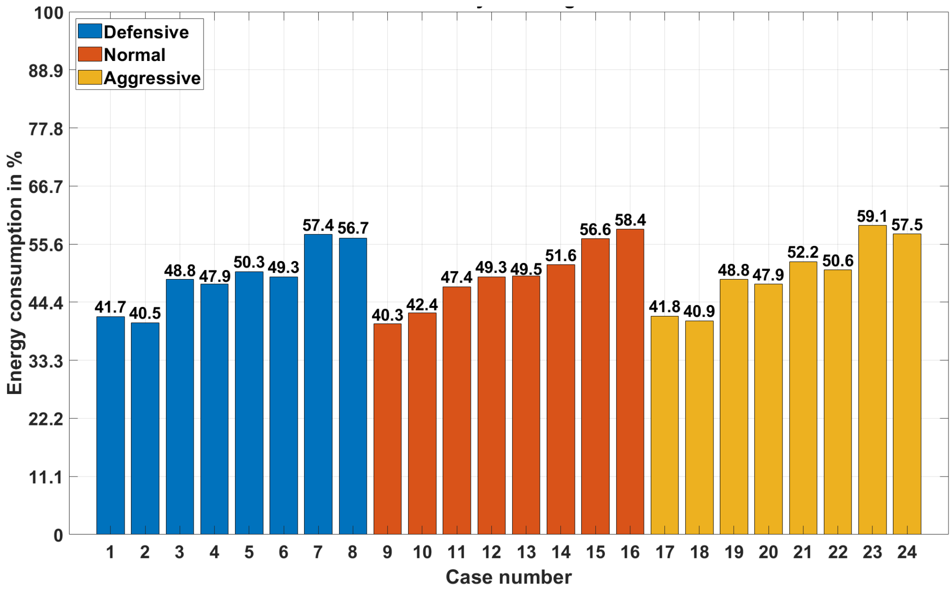

Figure 4.2: Energy consumption in motorway road segment (Normalised)

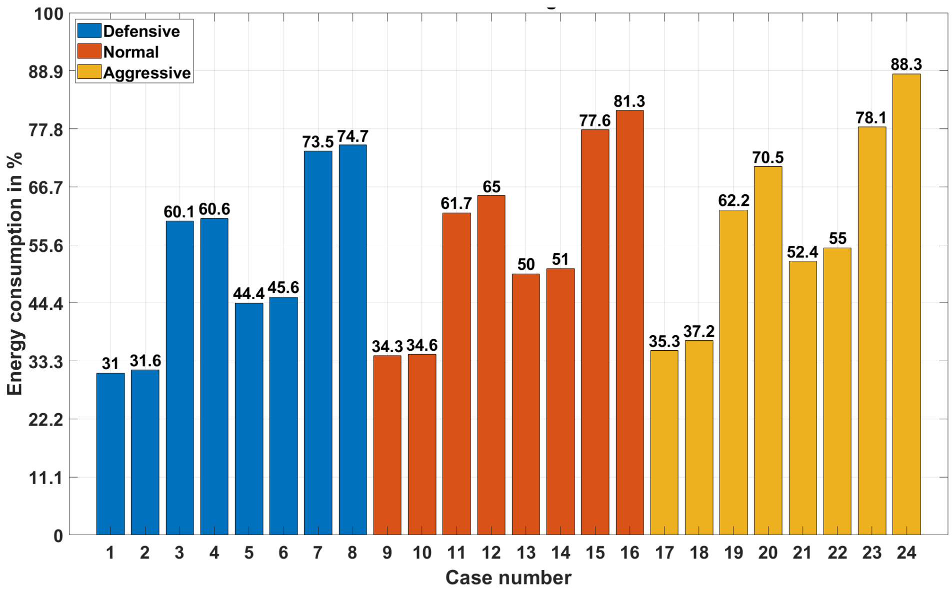

Figure 4.3: Energy consumption in urban road segment (Normalised)

4.2.1 Rural road segment

As mentioned above, the energy consumption for all the cases were arranged to understand the impact of parameters on energy consumption in different road segment. In this section energy consumption in rural road segment case setup is discussed. Figure 4.4, 4.5 and 4.6 represents normalised plot for energy consumption in rural road segment for defensive, normal and aggressive driver respectively.

The energy consumption for defensive driver in rural road segment is shown in the Figure 4.4. In order to determine the impact of traffic flow on the energy consumption for the same driver, traffic situation was changed from low traffic to rush hours traffic, while the rest of the parameters were unchanged it was found that the energy consumption increased with increase in traffic. It can also be observed that this trend remains true for all the driver behaviour, auxiliary load and mass cases. But, This trend was more evident when the driver behaviour was changed from defensive to normal driver and it was less evident when changed from Normal to aggressive driver behaviour. The possible reason for that might be the close proximity of drive cycle for normal and aggressive driver in comparison to the defensive driver as shown in Figure A.1 and A.3.

The Figure 4.7 represents the change in driver behaviour from defensive to normal and normal to aggressive whilst other parameter remains unchanged. This would indicate the effect of driver behaviour on energy consumption. It was observed that the impact of driver behaviour in rural road segment was very minimal when compared to effect of other parameters. This was mainly because of the relatively constant speed of the vehicle resulting in less acceleration and deceleration due to less traffic flow and fewer braking zones. Acceleration profile for the same is shown in Figure A.2 and A.4.

As we move from left to right in plot for mass 1 as shown in Figure 4.4, we compare the low load and low traffic case with high load and low traffic case, it represents the effect of load on energy consumption. It was observed that the impact of auxiliary load was constant for all the cases in rural road segment i.e, with change in load from low to high auxiliary load resulted in high energy consumption, this change in energy consumption is constant across all the test cases and driver behaviour. This was because the ambient temperature and load values were assumed to be constant for the all the cases and the duration of the drive cycle for the all the cases in rural road segment were almost the same.

As we move from left to right in Figure 4.4 i.e, mass 1 to mass 2 plot, we compare the change in mass from mass 1 to mass 2 and keeping the rest of the parameters unchanged for all the cases and for all the driver types. It represents the impact of change in mass on energy consumption. It was observed that, with change in mass from mass 1 to mass 2 resulted in more energy consumption. This change is energy consumption is constant in both low traffic and rush hour traffic for defensive driver. In case of normal and aggressive driver, impact of mass is marginally lower in case of low traffic compared to rush hours. Since acceleration and deceleration is lower for low traffic hours compared to rush hour traffic as shown in Figure A.2 and A.4, hence the energy consumption is higher for rush hour traffic. From Equation 2.3 it is evident that mass of the vehicle is directly proportional to traction force required to set the vehicle in motion. The increase in mass of the vehicle results in increase in traction force leading to higher torque demand on the wheels, hence the energy consumption is higher with increase in mass.

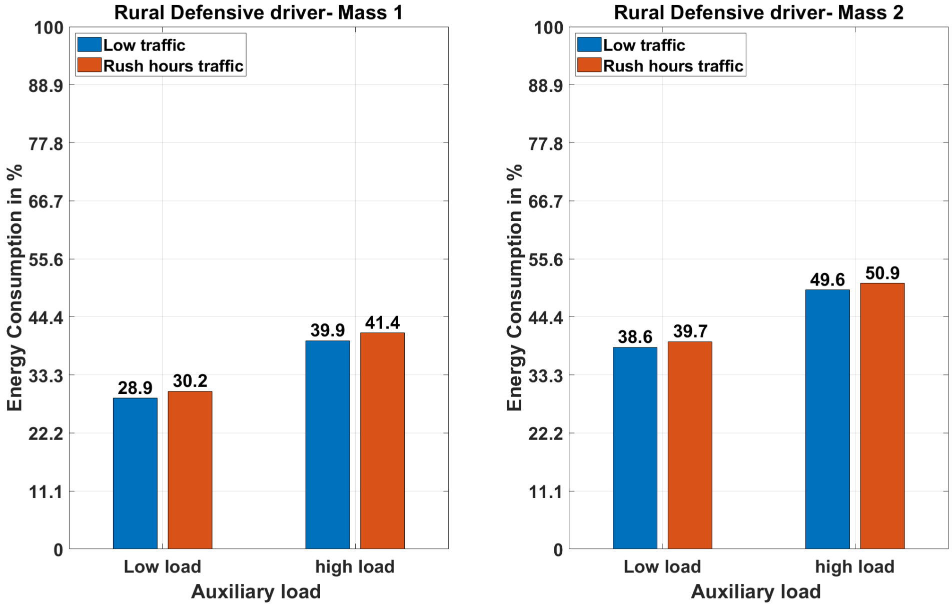

Figure 4.4: Energy consumption in rural road segment and defensive driver (Normalised)

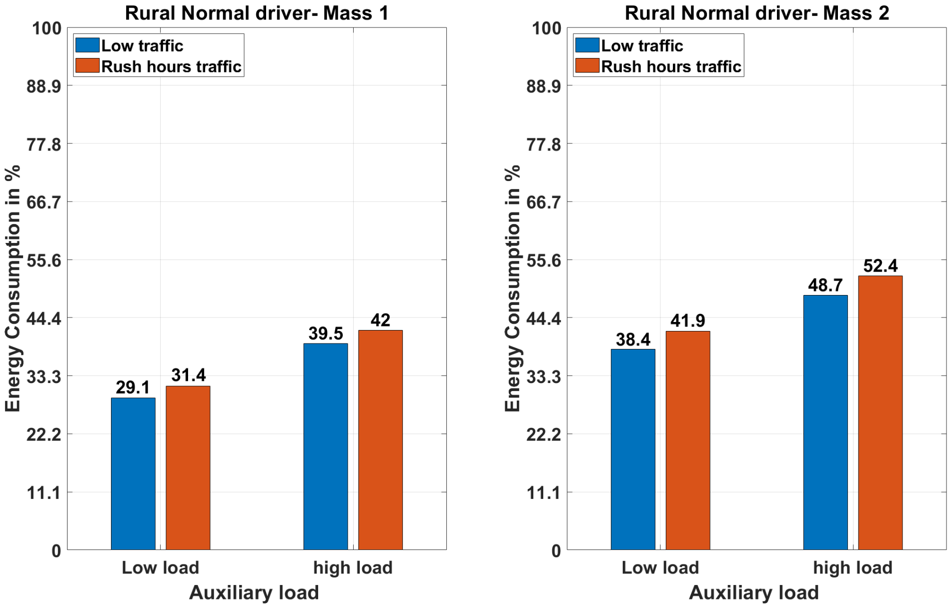

Figure 4.5: Energy consumption in rural road segment and normal driver (Normalised)

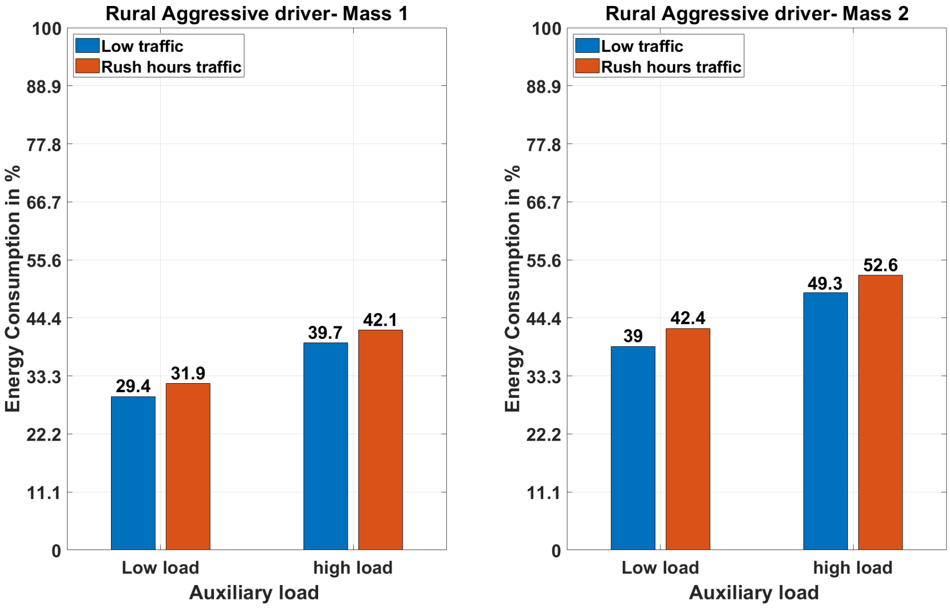

Figure 4.6: Energy consumption in rural road segment and aggressive driver (Normalised)

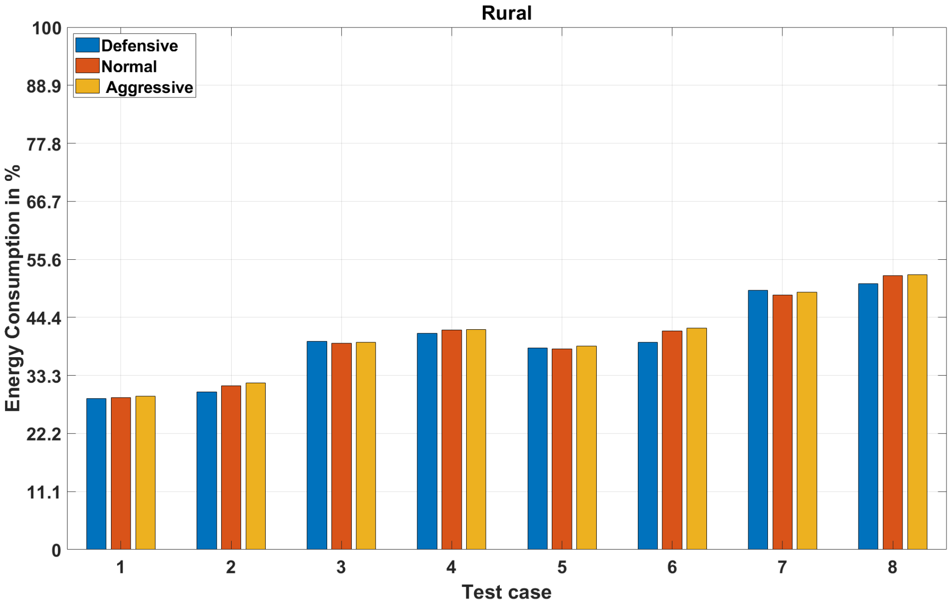

Figure 4.7: Effect of driver behaviour in rural road segment (Normalised)

4.2.2 Motorway road segment

The principle mentioned in subsection 4.2.1 were replicated to determine the impact of parameters on energy consumption in motorway road segment. Figure 4.8, 4.9, and 4.10 represents normalised plot for energy consumption in motorway road segment for defensive, normal, and aggressive driver respectively. It can be observed that energy consumption for all the cases in motorway road segment is higher than the energy consumption in rural road segment. The energy consumption in this road segment varies with in a small window.

In order to determine the impact of traffic flow on the energy consumption for the same driver, traffic situation was changed from low traffic to rush hours traffic, while the rest of the parameters were unchanged. It can be observed that energy consumption increased in case of normal driver when the traffic was changed from low traffic to rush hours traffic and this change in energy consumption is constant for all the test cases of normal driver. But, in case of defensive and aggressive driver it was observed that there was decrease in energy consumption when the traffic was changed from low traffic to rush traffic hours and remained the same for all the cases for defensive and aggressive driver. This is mainly because of change in traffic flow condition and interaction with the surrounding traffic when the driver behaviour was changed from defensive to normal and aggressive. It can be seen from Table A.4 and A.5 that when the traffic situation was changed from low traffic to rush hour traffic, there was an increase in average speed of normal driver. As we know from subsection 2.1.1 and Figure 2.2 aerodynamic force acting on vehicle increases with square of speed and it is the dominant force acting at high speeds on vehicle. So with increase in average speed for normal driver in high traffic hours energy consumption increases. Where as in case of defensive and aggressive driver it can be observed from Table A.4 and A.5 that there was decrease in average speed when traffic conditions changed from low traffic to rush traffic hours resulting in decreased energy consumption.

The Figure 4.11 represents the change in driver behaviour from defensive to normal and normal to aggressive whilst other parameter remains unchanged. This would indicate the effect of driver behaviour on energy consumption. As mentioned earlier there was change in traffic flow condition and interaction with the surrounding traffic when the driver behaviour was changed from defensive to normal and aggressive. Hence had a impact on energy consumption. The impact on energy consumption was higher than that of in rural road segment.

As we move from left to right in plot for mass 1 as shown in Figure 4.8, we compare the low load and low traffic case with high load and low traffic case, it represents the effect of load on energy consumption. It was observed that the impact of the auxiliary load on energy consumption was constant in motorway road segment i.e, with change in auxiliary load from low to high resulted in higher energy consumption. This change in energy consumption is constant for all the cases and driver behaviour in motorway road segment and this is because of the principle mentioned in subsection 4.2.1.

As we move from left to right in Figure 4.8 i.e, mass 1 to mass 2 plot, we compare the change in energy consumption when mass was changed from mass 1 to mass 2 and keeping the rest of the parameters unchanged for all the cases and for all the driver types. It represents the impact of change in mass on energy consumption. It was observed that, with change in mass from mass 1 to mass 2 resulted in more energy consumption. This energy consumption is constant for all load cases and driver in motorway road segment and this is because of the principle mentioned in subsection 4.2.1.

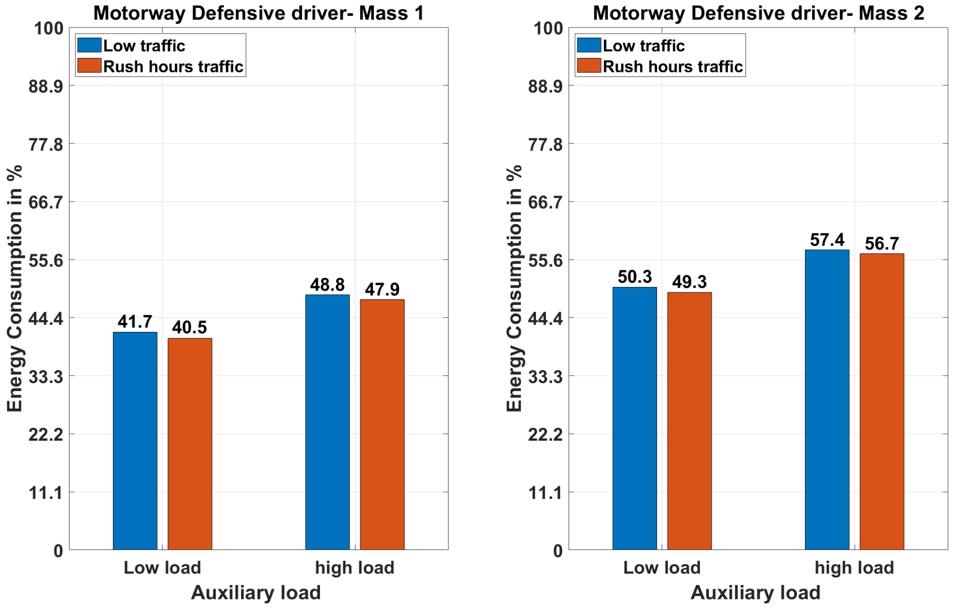

Figure 4.8: Energy consumption in motorway road segment and defensive driver (Normalised)

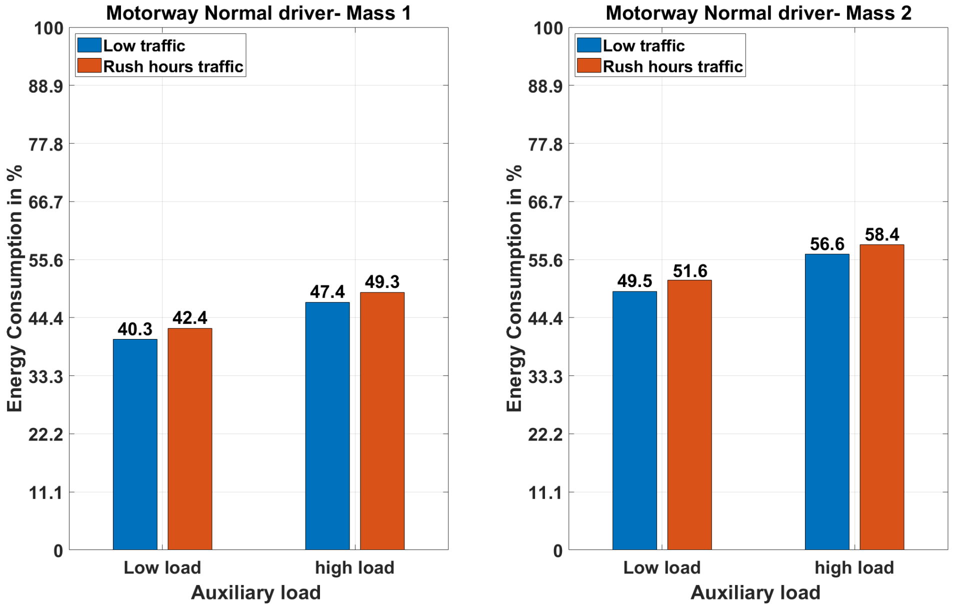

Figure 4.9: Energy consumption in motorway road segment and normal driver (Normalised)

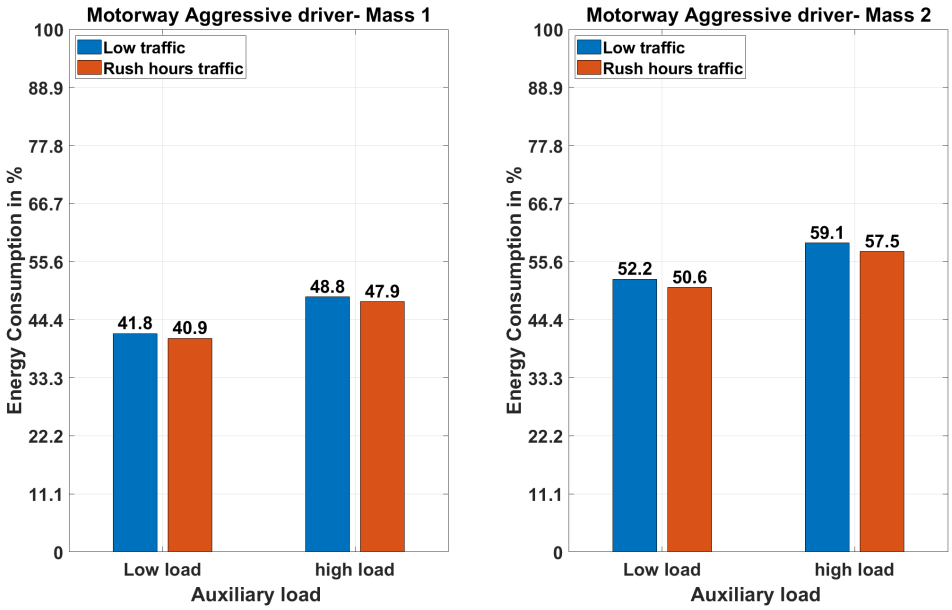

Figure 4.10: Energy consumption in motorway road segment and aggressive driver (Normalised)

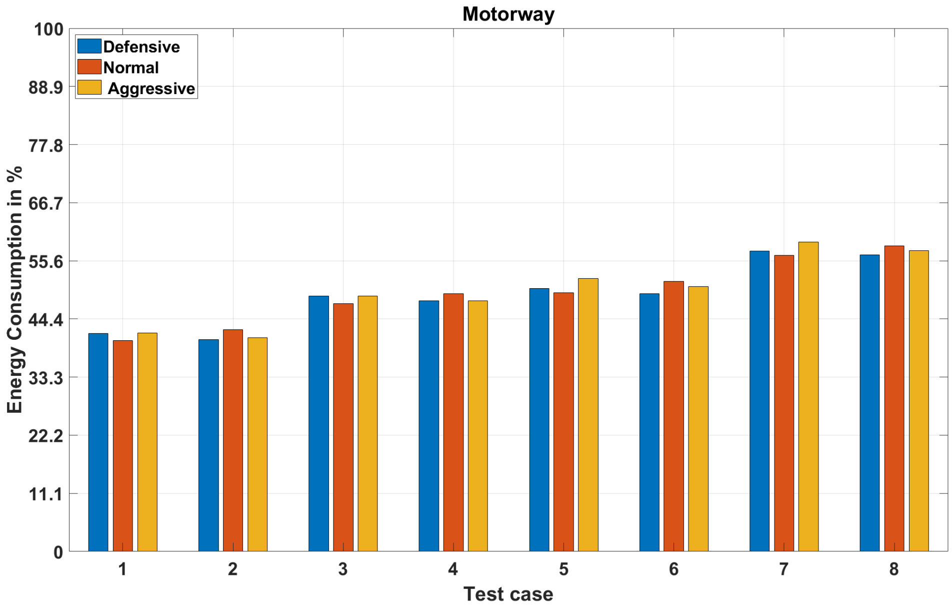

Figure 4.11: Effect of driver behaviour in motorway road segment (Normalised)

4.2.3 Urban road segment

The principle mentioned in subsection 4.2.1 were replicated in urban road segment to determine the impact of parameters on energy consumption. Figure 4.12, 4.13, and 4.14 represents normalised plot for energy consumption in urban road segment for defensive, normal, and aggressive driver respectively. It can be observed that energy consumption for all the cases in urban road segment is higher than the energy consumption in rural and motorway road segment. Impact of each parameter mentioned above on energy consumption is discussed below.

As we move from left to right for low load in plot for mass 1 as shown in Figure 4.12, it determines the impact of traffic flow on the energy consumption, when traffic situation was changed from low traffic to rush hours traffic for the same driver, while the rest of the parameters were unchanged. It was observed that energy consumption for defensive driver increased with increase in auxiliary load and vehicle mass but the change in energy consumption when traffic situation was changed was constant. Where as in case of normal and aggressive driver the trend of increase in energy consumption with increase in auxiliary load and vehicle mass continued along with increase in energy consumption when traffic situation was changed. It is observed that the interaction of ego with surrounding traffic in case of defensive driver was minimal. But, the traffic interaction of ego vehicle increased in the case of normal driver and it further increased in case of the aggressive driver resulting in frequent acceleration and deceleration which in turn resulted in more energy consumption.

The Figure 4.15 represents the change in driver behaviour from defensive to normal and normal to aggressive whilst other parameter remains unchanged. This would indicate the effect of driver behaviour on energy consumption. It was observed that there was change in interaction of the ego vehicle and surrounding traffic when driver behaviour was changed. When driver behaviour was changed from defensive to aggressive driver resulted in increase in energy consumption and the impact was consistent throughout. But, when the driver behaviour was changed from normal to aggressive driver it was observed that the energy consumption was less in low traffic when compared to rush hours traffic and this was consistent for all the load and mass cases.

As we move from left to right in plot for mass 1 as shown in Figure 4.12, we compare the low load and low traffic case with high load and low traffic case, it represents the effect of load on energy consumption. It was observed that the impact of auxiliary load on energy consumption was constant for defensive driver type, where as for normal and aggressive driver type it was observed that the energy consumption due auxiliary load was more in rush traffic hours than that of in low traffic hours. As mentioned in subsection 4.2.1 auxiliary load and ambient temperature were assumed to be constant and it can be seen from Table A.6 and A.7 time duration for defensive driver in both the traffic condition were almost equal resulting in constant energy consumption because of auxiliary load.

For normal and aggressive driver it can be seen from Table A.6 and A.7 that the duration for low traffic hours was less than that in rush hours traffic. So, more energy was consumed in rush traffic hours than that in low traffic hours.

As we move from left to right in Figure 4.12 i.e, mass 1 to mass 2 plot, we compare the change in energy consumption when mass was changed from mass 1 to mass 2 and keeping the rest of the parameters unchanged for all the cases and for all the driver types. It represents the impact of change in mass on energy consumption. It was observed that, with change in mass from mass 1 to mass 2 resulted in more energy consumption. This is because of the principle mentioned in subsection 4.2.1. This increase in energy consumption is constant for both load cases in defensive driver and it was also observed that as the driver behaviour was changed from defensive to normal and normal to aggressive resulted in increase in energy consumption. This is because the change in driver behaviour resulted in frequent aggressive acceleration and deceleration, which in turn demanded more energy at the wheels resulting in more energy consumption.

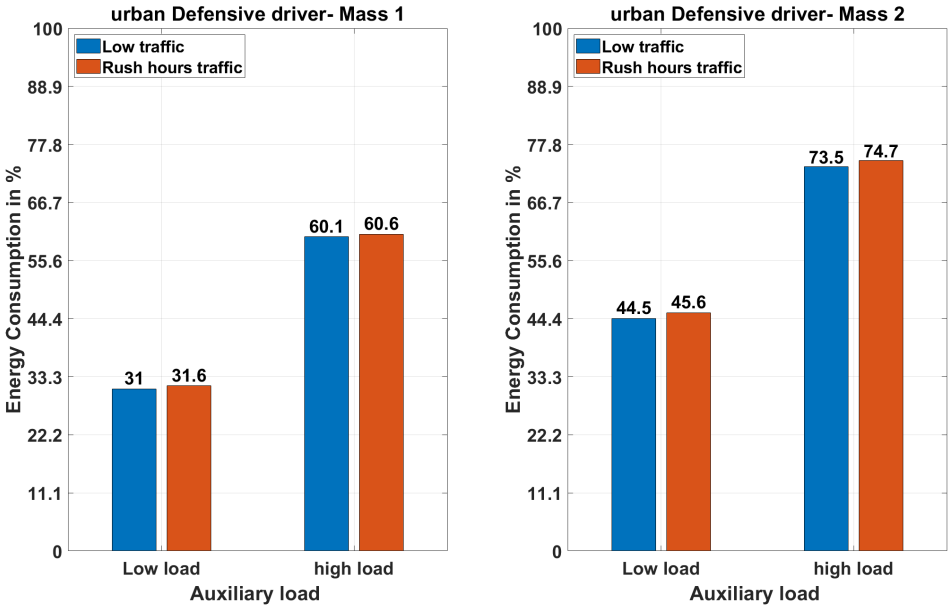

Figure 4.12: Energy consumption in Urban road segment and defensive driver (Normalised)

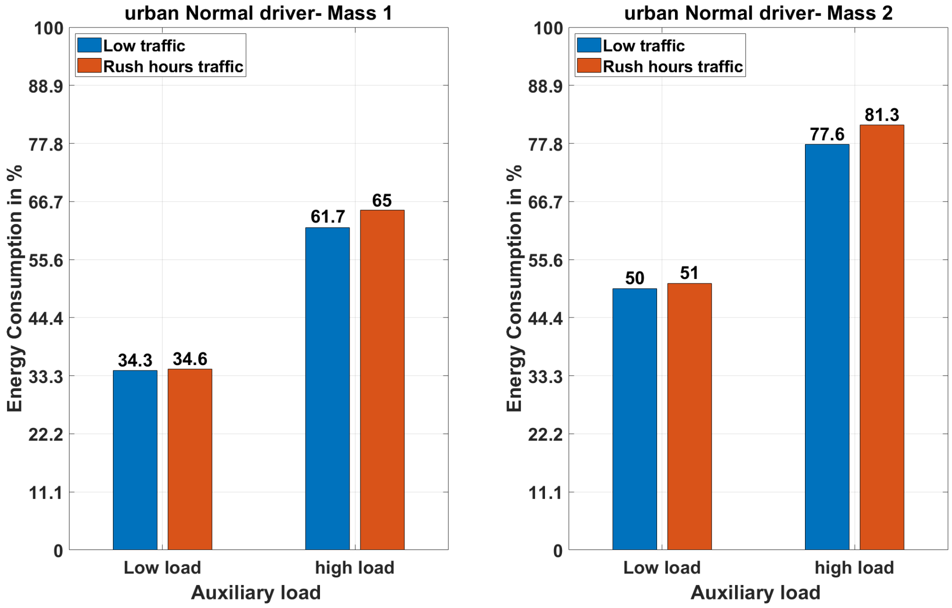

Figure 4.13: Energy consumption in Urban road segment and normal driver (Normalised)

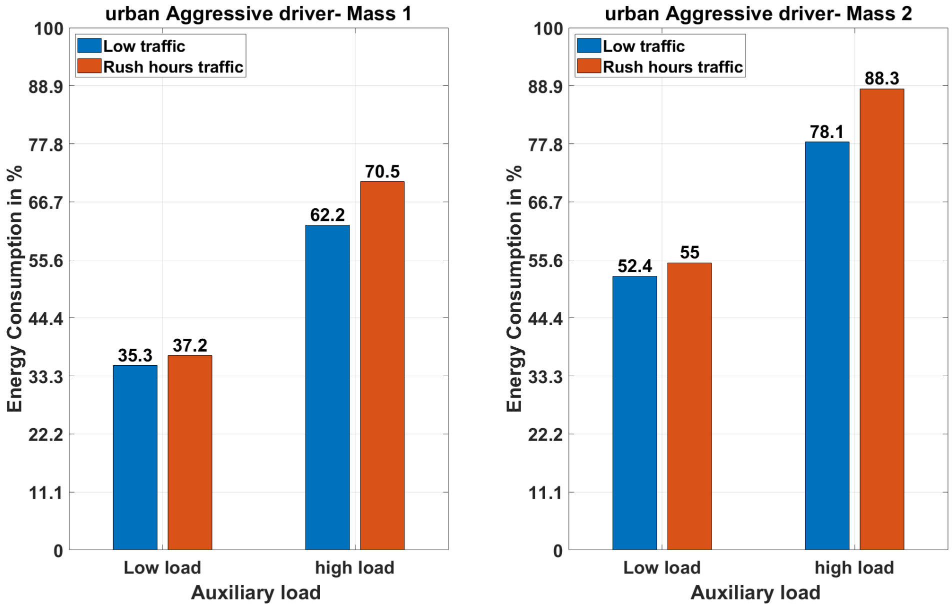

Figure 4.14: Energy consumption in Urban road segment and aggressive driver(Normalised)

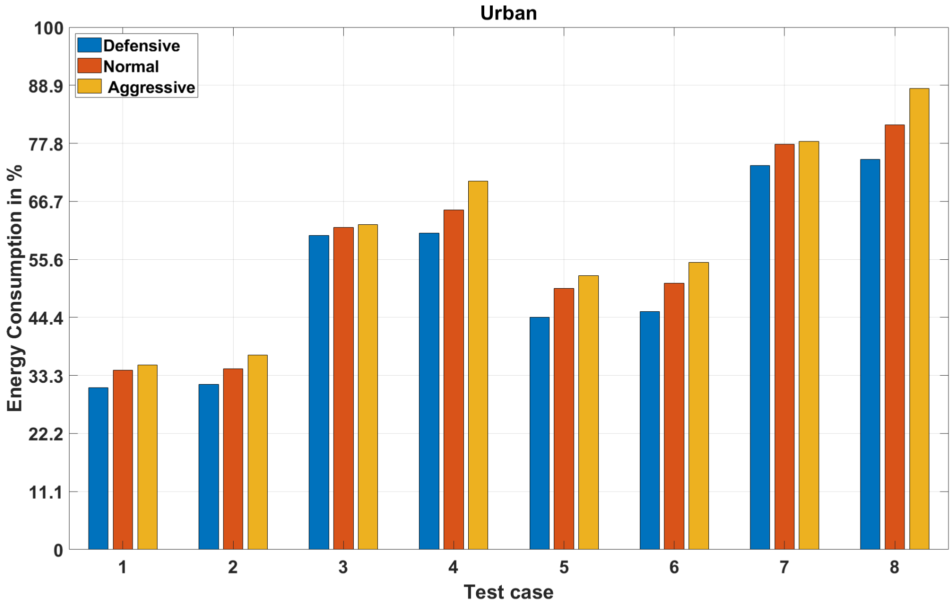

Figure 4.15: Effect of driver behaviour in urban road segment (Normalised)

5

Conclusion and Future Work

5.1 Conclusion

In this thesis, to determine the impact of driver behaviour and traffic situation on BEV range in different road segments, traffic simulation model for the selected route for different road segments from RDE CEVT route has been developed in SUMO to capture real world factors like driver behaviour and traffic situation. Output from traffic simulation was fed as input to vehicle model built in Carmaker to determine the energy consumption. The results have shown that these factor had impact on energy consumption of BEV. Quantitatively energy consumption was higher in case of urban road segment followed by motorway and rural road segment. Impact of traffic situation was more in urban road segment followed by rural and motorway road segment. Impact of driver behaviour on energy consumption was more in Urban road segment followed by motorway and rural road segment. Impact of auxiliary load and mass was higher in urban road segment followed by rural and motorway road segment.

5.2 Future Work

The presented results holds good for the assumption and recommendation made during the work. But in order to build a more accurate model to capture the real world factors there are few improvements to be made. These improvements are mentioned below.

5.2.1 Vehicle model in SUMO

In SUMO, it was found that the ego vehicle in Curved road tends to move at a constant speed but it was observed from the test drive in the same road segment that the driver tends to brake a little to reduce the vehicle speed to avoid run off of the vehicle. This variation is observed mainly because of primitive vehicle model in SUMO and this can by rectified by modifying the stochastic vehicle model in SUMO or using co-simulation frame work.

5.2.2 Co-simulation SUMO Carmaker

In this thesis work, a frame work was created where the output file from traffic simulation was manually fed to vehicle model in Carmaker. The vehicle model was forced to follow the drive cycle obtained from traffic simulation on a straight road. Here, the effect of steering losses due to turning is neglected. The next step in this development process would be to create a co-simulation framework of SUMO and Carmaker, there by bringing the best of both worlds i.e, realistic traffic flow from SUMO and accurate vehicle model from Carmaker. This would result in a more accurate model to capture real world factors like driver behaviour and traffic situation leading to better estimation of impact of these parameters on range of BEV.

5.2.3 Altitude profile

The altitude profile for all the road segment mentioned earlier were assumed to be constant. This was done to decrease the complexity of creating altitude profile in both the simulation environment and also due to inaccurate elevation data of the road. It was found from literature survey that this is an important factor in road network and had an impact on overall energy consumption of the vehicle. Hence it is important to consider this in future work to match the real world factors and investigate its impact on energy consumption.

5.2.4 Traffic flow data

The traffic flow data is used to vary the traffic situation. It was observed that the traffic vehicles were entering into traffic simulation environment with the constant interval between successive vehicles. The constant interval was dependent on the traffic flow. But, this is not the case in real world traffic. This can be improved by using real-time data like origin-Destination-Matrices, turning ratios and data from detectors. These data types are also supported by SUMO.

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A

Appendix 1

Case number	**Driver style**	**Mass**	**Auxiliary load**	**Traffic cognition**
Case 1	Defensive	1500	High load	Low traffic hours
Case 2	Defensive	1500	High load	Rush hours
Case 3	Defensive	1500	Low load	Low traffic hours
Case 4	Defensive	1500	Low load	Rush hours
Case 5	Defensive	2500	High load	Low traffic hours
Case 6	Defensive	2500	High load	Rush hours
Case 7	Defensive	2500	Low load	Low traffic hours
Case 8	Defensive	2500	Low load	Rush hours
Case 9	Normal	1500	High load	Low traffic hours
Case 10	Normal	1500	High load	Rush hours
Case 11	Normal	1500	Low load	Low traffic hours
Case 12	Normal	1500	Low load	Rush hours
Case 13	Normal	2500	High load	Low traffic hours
Case 14	Normal	2500	High load	Rush hours
Case 15	Normal	2500	Low load	Low traffic hours
Case 16	Normal	2500	Low load	Rush hours
Case 17	Aggressive	1500	High load	Low traffic hours
Case 18	Aggressive	1500	High load	Rush hours
Case 19	Aggressive	1500	Low load	Low traffic hours
Case 20	Aggressive	1500	Low load	Rush hours
Case 21	Aggressive	2500	High load	Low traffic hours
Case 22	Aggressive	2500	High load	Rush hours
Case 23	Aggressive	2500	Low load	Low traffic hours
Case 24	Aggressive	2500	Low load	Rush hours

Table A.1: Case setup for rural, urban and motorway road segement.

A.1 Drive cycle

A.1.1 Rural road segment

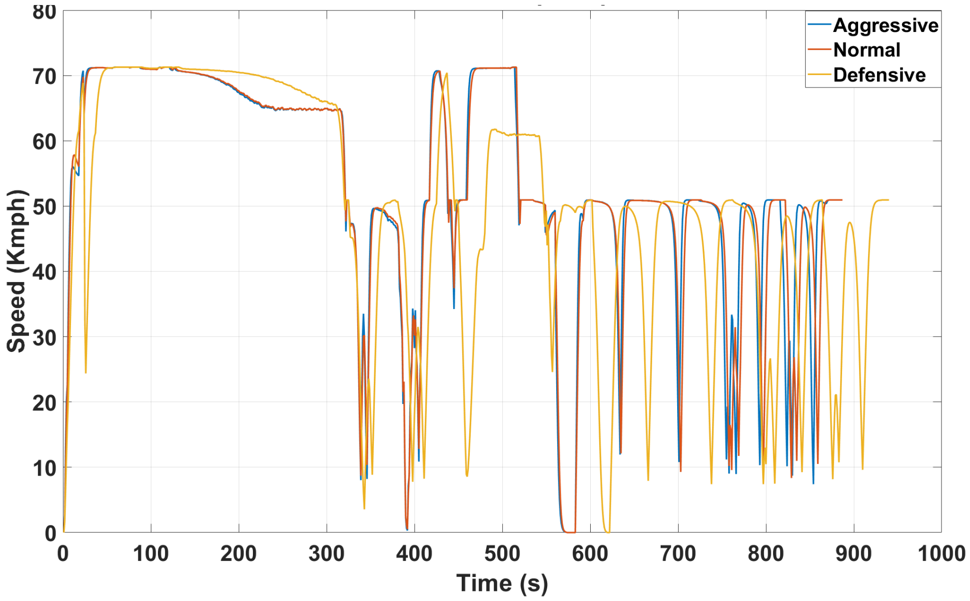

Figure A.1: Rural low traffic speed profile.

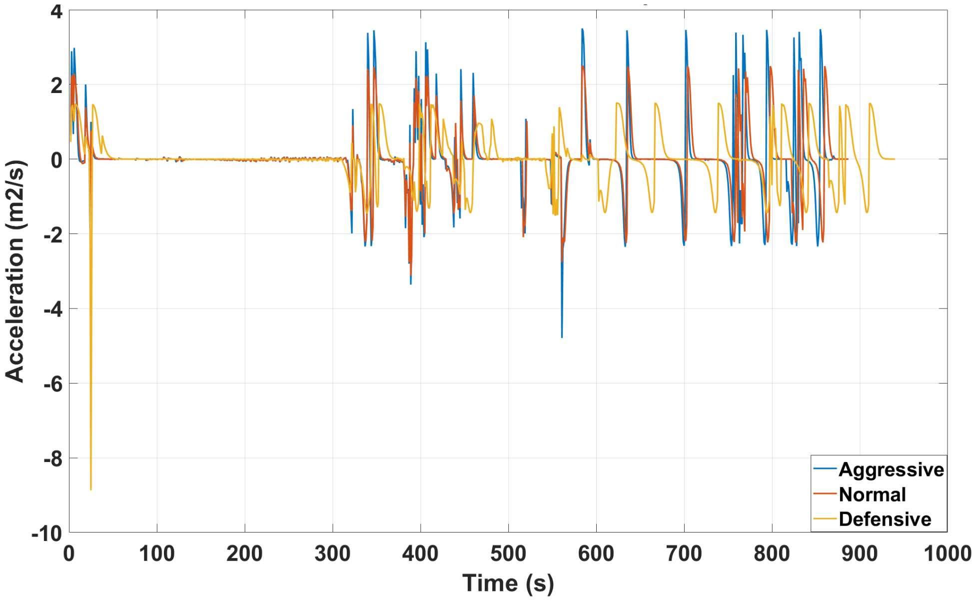

Figure A.2: Rural low traffic acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	940	887	882
Stop duraction, sec	4	11	11
Distance, m	13200	13200	13200
Maximum speed, km/h	71.2	71.28	71.28
Average speed without stops, km/h	50.2	53.62	53.95
Average speed with stops, km/h	49.99	52.95	53.28

Table A.2: Rural low traffic DC Parameters

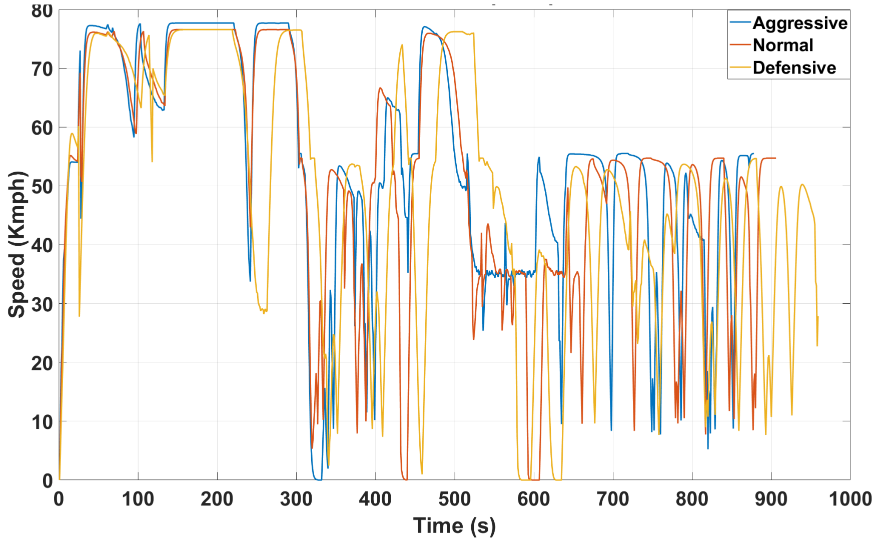

Figure A.3: Rural rush hours speed profile.

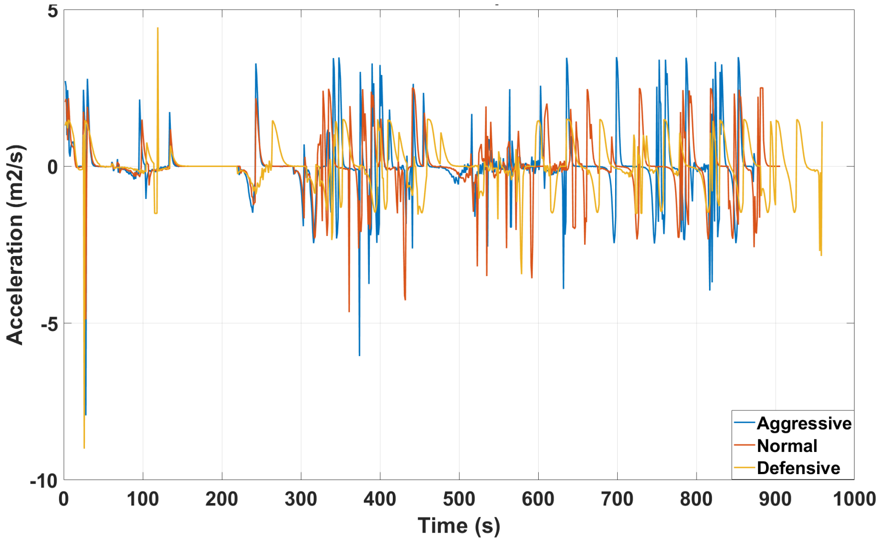

Figure A.4: Rural rush hours acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	959	906	878
Stop duraction, sec	21	12	6
Distance, m	13200	13200	13200
Maximum speed, km/h	76.57	76.57	77.68
Average speed without stops, km/h	49.97	52.59	53.89
Average speed with stops, km/h	48.88	51.89	53.52

Table A.3: Rural rush hours DC Parameters

A.1.2 Motorway road segment

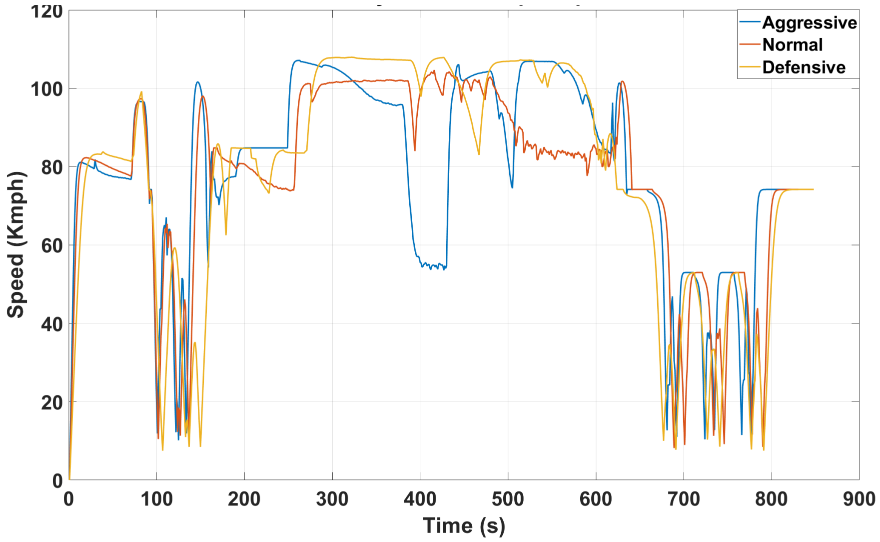

Figure A.5: Motorway low traffic speed profile.

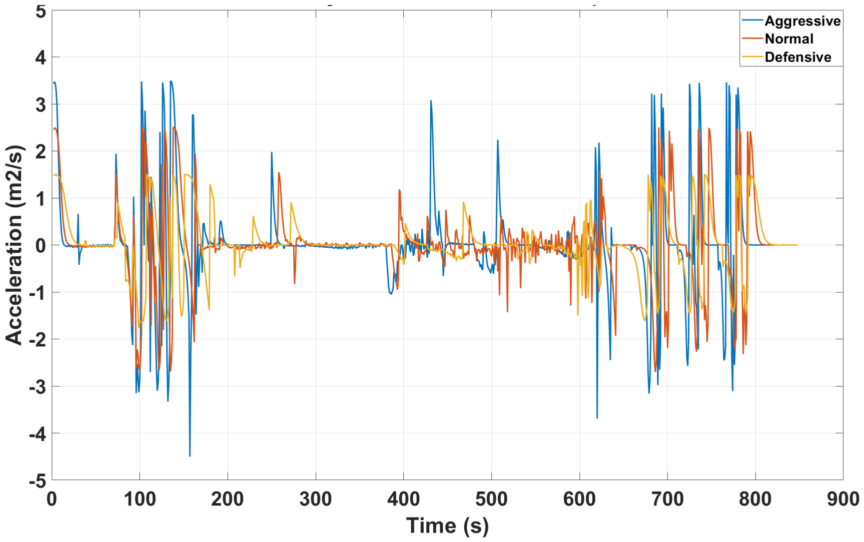

Figure A.6: Motorway low traffic acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	848	845	831
Stop duraction, sec	1	1	1
Distance, m	18200	18200	18200
Maximum speed, km/h	107.92	104.65	107.1
Average speed without stops, km/h	77.65	77.95	79.29
Average speed with stops, km/h	77.56	77.86	79.2

Table A.4: Motorway low traffic DC Parameters

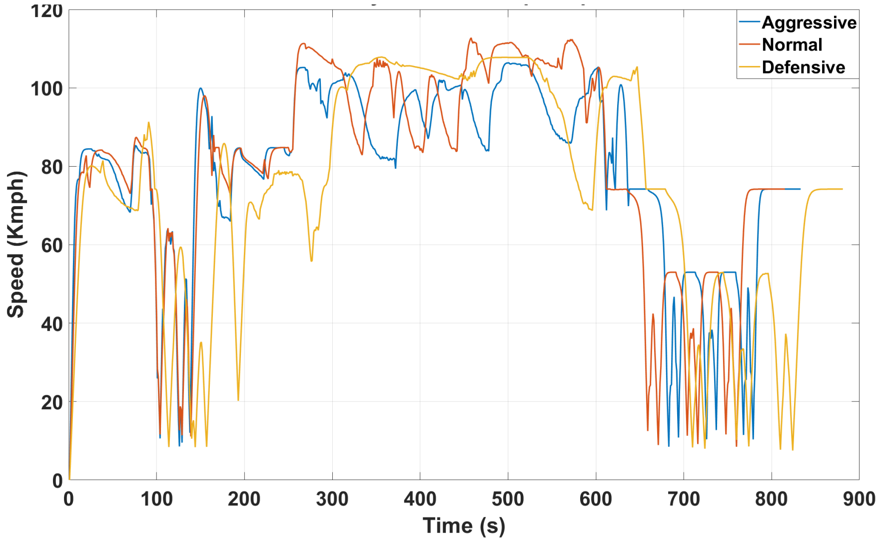

Figure A.7: Motorway rush hours speed profile.

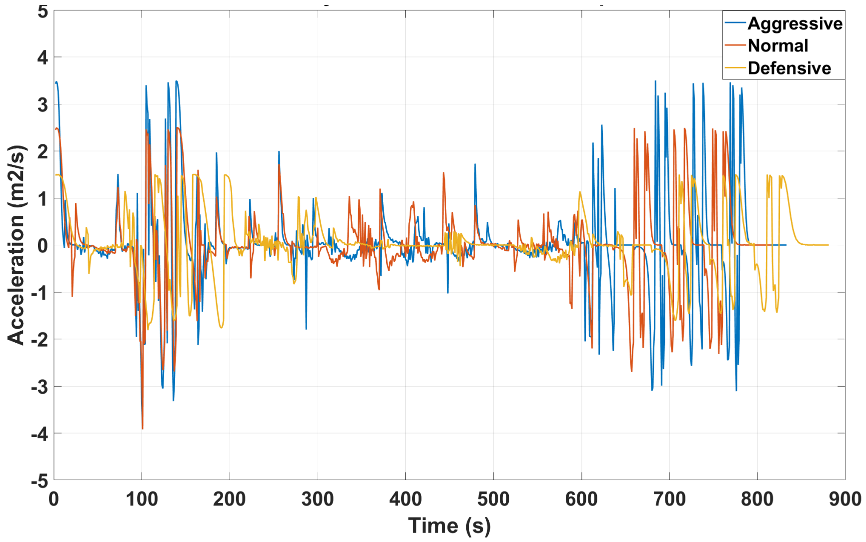

Figure A.8: Motorway rush hours acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	881	815	833
Stop duraction, sec	1	1	1
Distance, m	18200	18200	18200
Maximum speed, km/h	107.85	112.75	106.38
Average speed without stops, km/h	74.74	80.82	76.15
Average speed with stops, km/h	74.65	80.72	76.08

Table A.5: Motorway rush hours DC Parameters

A.1.3 Urban road segment

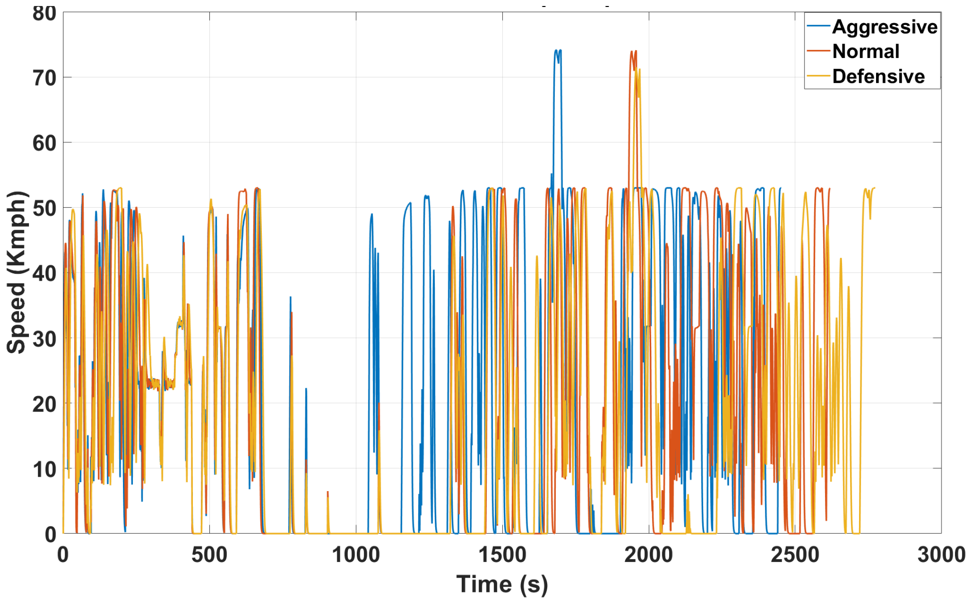

Figure A.9: Urban low traffic speed profile.

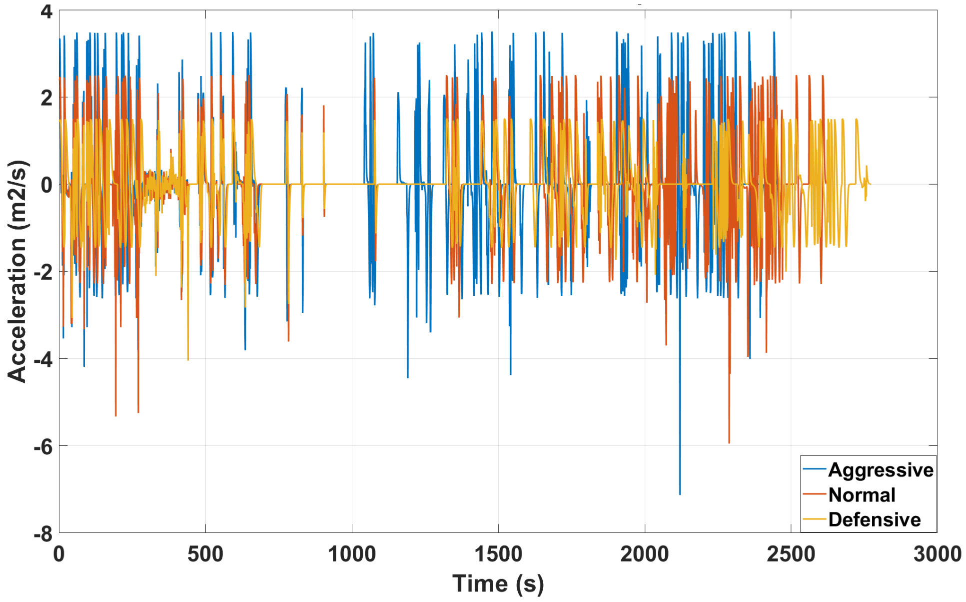

Figure A.10: Urban low traffic acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	2773	2619	2452
Stop duraction, sec	994	922	782
Distance, m	13400	13400	13400
Maximum speed, km/h	71.49	74.08	74.16
Average speed without stops, km/h	29.4	30.93	31.32
Average speed with stops, km/h	18.86	19.98	21.33

Table A.6: Urban low traffic DC Parameters

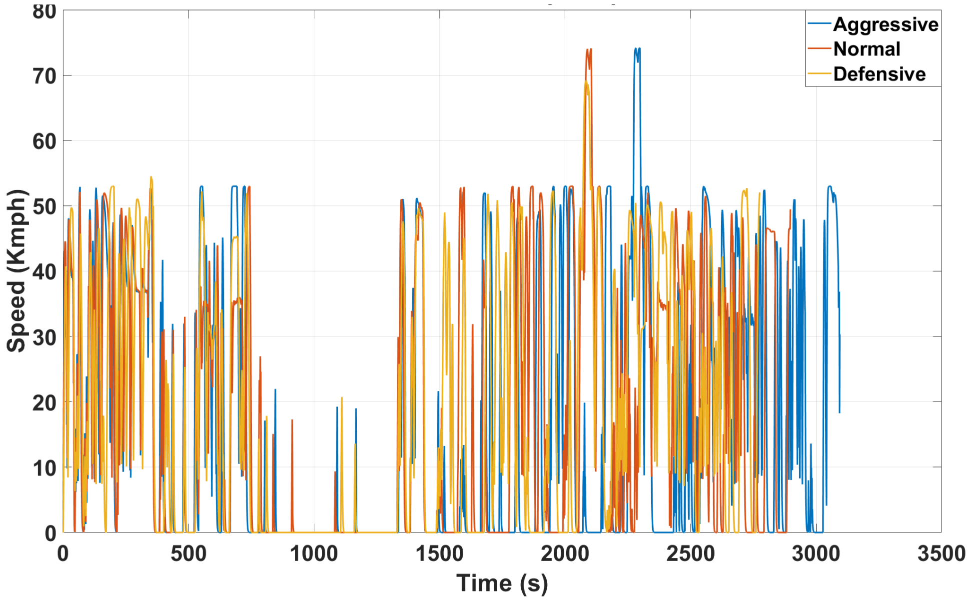

Figure A.11: Urban rush hours speed profile.

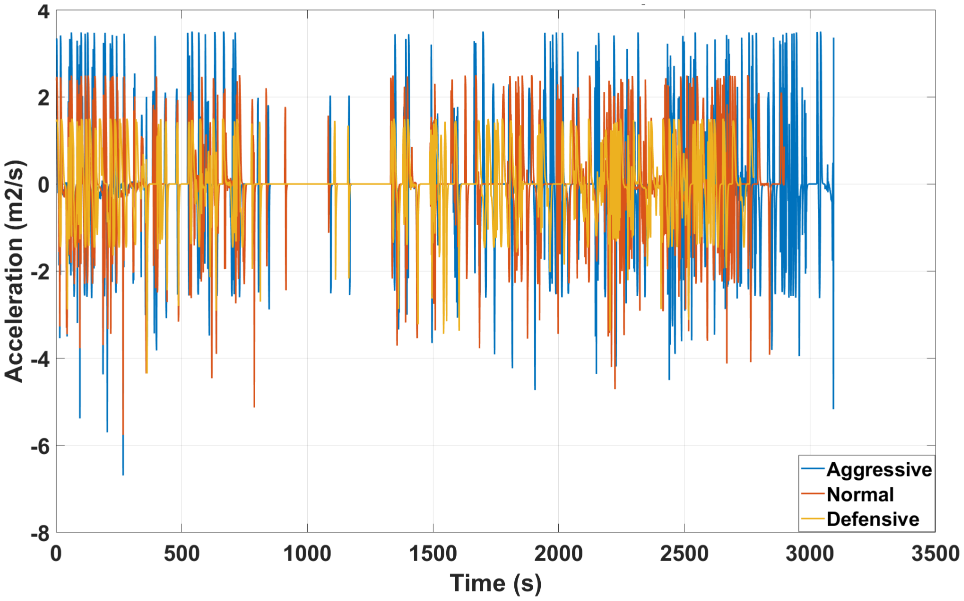

Figure A.12: Urban rush hours acceleration profile.

Parameters	Defensive	Normal	Aggressive
Duration, sec	2775	2897	3094
Stop duraction, sec	934	1020	1237
Distance, m	13400	13400	13400
Maximum speed, km/h	69.19	74.08	74.16
Average speed without stops, km/h	28.41	27.86	28.15
Average speed with stops, km/h	18.84	18.05	16.9

Table A.7: Urban rush traffic DC Parameters