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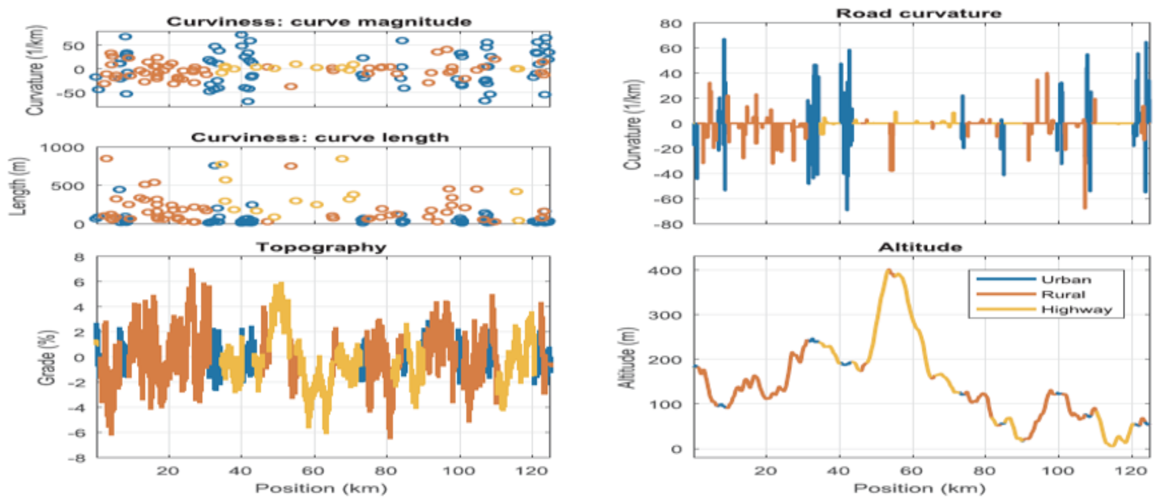
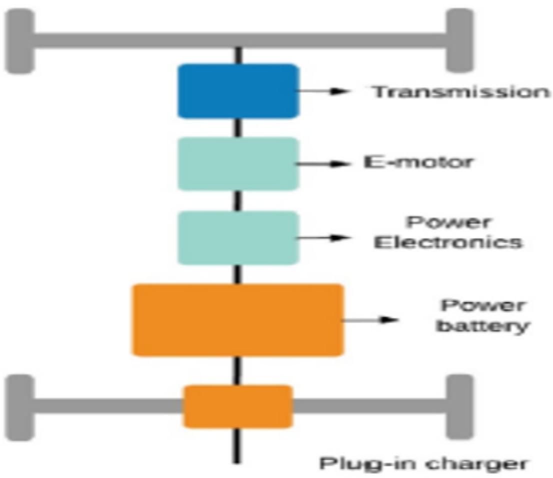
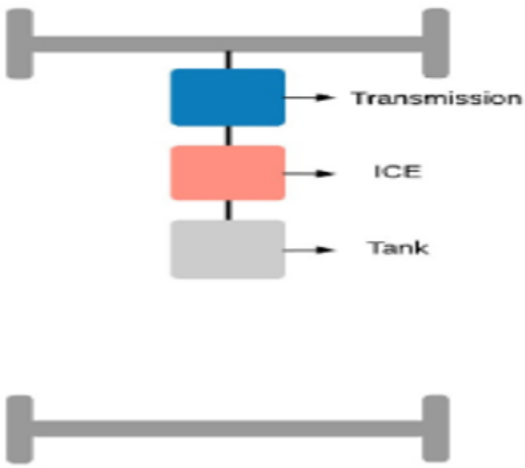
Master Thesis Project Report

" Assessment of environmental parameters on energy efficiency for different heavy vehicles powertrains using the operating cycle format"







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Project title: "Assessment of environmental parameters on energy efficiency for different heavy vehicles powertrains using the operating cycle format".

"This project was made in collaboration with a research group (COVER) at Chalmers".

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ABSTRACT

Energy efficiency is easily influenced by various environmental factors, for example, road conditions, weather, etc. Understanding the environmental impact on a vehicle's energy consumption is essential in developing and assigning a suitable truck for the right task. There is a great potential for energy-saving if the real-world case studies of the transportation operating environment are examined, with factors such as road slope, legal speed, and curviness. This project investigates the energy utilization of BEV & ICE vehicle drivetrain parameters.

Heavy-duty vehicles have a greater mass, and high drag coefficient compared to light-duty vehicles or passenger cars. These have a significant impact on energy consumption, making it an ideal choice to evaluate topography, legal speeds, and road curvature parameters. The main finding shows the impact of these environmental model parameters on energy consumption for various powertrain parameters such as battery size, motor efficiencies, and engine operating points.

Finally, to forecast how each parameter influences energy trends, a relationship has been established between external variables and drivetrain parameters. In addition, a study was carried out to determine which parameters of the curvature and topographical models have the largest influence on energy.

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CONTENTS

ABBREVIATIONS

C	Curvature	[m]
e	Error term (for topography)	[-]
E_{Curv}	Curvature energy consumption	[kWh]
E_{Top}	Topography energy consumption	[kWh]
E_{Tot}	Total energy consumption	[kWh]
E_0	Flat road energy consumption	[kWh]
F_{air}	Air resistance	[N]
F_{grade}	Grade resistance	[N]
F_x	Longitudinal force	[N]
F_{roll}	Rolling resistance	[N]
k_{min}	Minimal curvature threshold value	[m^{-1}]
L	Curve length	[m]
L_{h}	Hill length	[m]
L_{s}	Road segment length	[m]
L_{speed}	Legal speed	[ms^{-1}]
L_{tot}	Total mission distance	[m]
m	Mass of the vehicle	[kg]
n	Number of states	[-]
N	Normal distribution	[-]
p	Any physical quantity	[-]
p_{aux}	Power for auxiliaries	[W]
p_{drive}	Power for driving	[W]
P_{tot}	Total power	[W]
P_{PTO}	Power take-off	[W]
Q_{T}	Unit energy consumption	[Jkg^{-1} m^{-1}]
r_{turn}	Minimum turn radius	[m]
R^2	Root mean square	[-]
v_x	Longitudinal speed	[ms^{-1}]
x, X	Longitudinal position, regressor	[-]
Y	Road gradient	[-]
z	Amplitude	[m]
ϵ	Residual	[-]
η	Efficiency	[-]
λ_{C}	Intensity of curves	[km^{-1}]

μ_{C}	Log-normal mean of (shifted) radius	[ln(m)]
μ_{L}	Expectation value of curve length	[ln(m)]
n'_C	Expected number of curves	[-]
ϕ_Y	Autoregression parameter	[-]
σ_{C}	Log-normal standard deviation of (shifted) radius	[ln(m)]
σ_e	Error amplitude	[-]
σ_{L}	Standard deviation of curve length	[ln(m)]
σ_{Y}	Topography amplitude	[%]

ACRONYMS

BEV	Battery Electric Vehicle
COVER	Real World CO_2 Assessment and Vehicle Energy Efficiency
dOC	Deterministic Operating Cycle
EV	Electric Vehicle
GTA	Global Transport Application
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
OC	Operating Cycle
sOC	Stochastic Operating Cycle
VECTO	Vehicle Energy Consumption Calculation Tool
VehProp	Vehicle Propulsion

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INTRODUCTION

1.1 Background

One of the key forces for technical growth and innovation in the automotive and road transport sectors is the need to minimize vehicle fuel consumption and carbon dioxide emissions (CO_2) [1]. International legislation has been reached to address the issue of automobile emissions, and limitations have been imposed. Where the methods differ among vehicle categories, official tests have been created to guarantee that these restrictions are observed. A chassis dynamometer is used to evaluate cars and light trucks in an experimental setting [2], [3]. During these tests, a certain target speed is set while emissions and energy consumption are tracked.

To test heavy-duty vehicles, the European Commission has developed a new simulation tool called “Vehicle Energy Consumption calculation TOol – VECTO”. To better reflect the actual European fleet, five separate mission profiles for trucks and five different mission profiles for buses and coaches have been devised and integrated with the program. Rolling resistance, air drag, masses and inertias, gearbox friction, auxiliary power, and engine performance are just a few of the factors given as input when predicting energy consumption and CO_2 emissions using VECTO on standardized driving cycles [4], [5]. Given that it just requires regular driving cycles (such as long haul, urban and regional deliveries, construction, and so on) as a velocity over time, it is evident that this is a highly simplified description when compared to real-world functioning.

To overcome this the Vehicle Dynamics group at Chalmers University is working on a project called “COVER-Real world CO_2 assessment and Vehicle enERgy efficiency”. The focus of this project is to develop methodologies and processes for the assessment and reduction of energy consumption in future vehicle generations, considering real vehicle operations [6]. To achieve this, researchers at Chalmers have an Operating Cycle (OC) as a replacement for conventional driving cycles. Indeed, these only describe speed as a function of time. Conversely, the OC includes the essentials of the road, weather, traffic, and mission that are needed to describe the behavior of the vehicle interaction with environmental parameters [7]. It helps in analyzing the vehicle energy consumption more completely and comprehensively.

The OC format is segregated into three levels of representation. The first representation, which includes a high-level description with very less details, helps in classifying the similarities and differences between the transport operations. The second, being the Stochastic Operating Cycle (sOC) format and falling under the mid-level description, is beneficial in reproducing the variation for individual transport missions with a more detailed statistical representation. Finally, the third representation is a low-level description that contains environmental parameters information in a detailed manner which is beneficial for vehicle operations [8]. Starting from a fully parametrized sOC, multiple Deterministic Operating Cycles (dOCs) may be generated as shown in Figure 1(a) and fed in as an input to the driver and vehicle subsystems. This can be seen in Figure 1(b). Further details about the Operating Cycle format and Vehicle Modeling will be discussed in the following chapters.

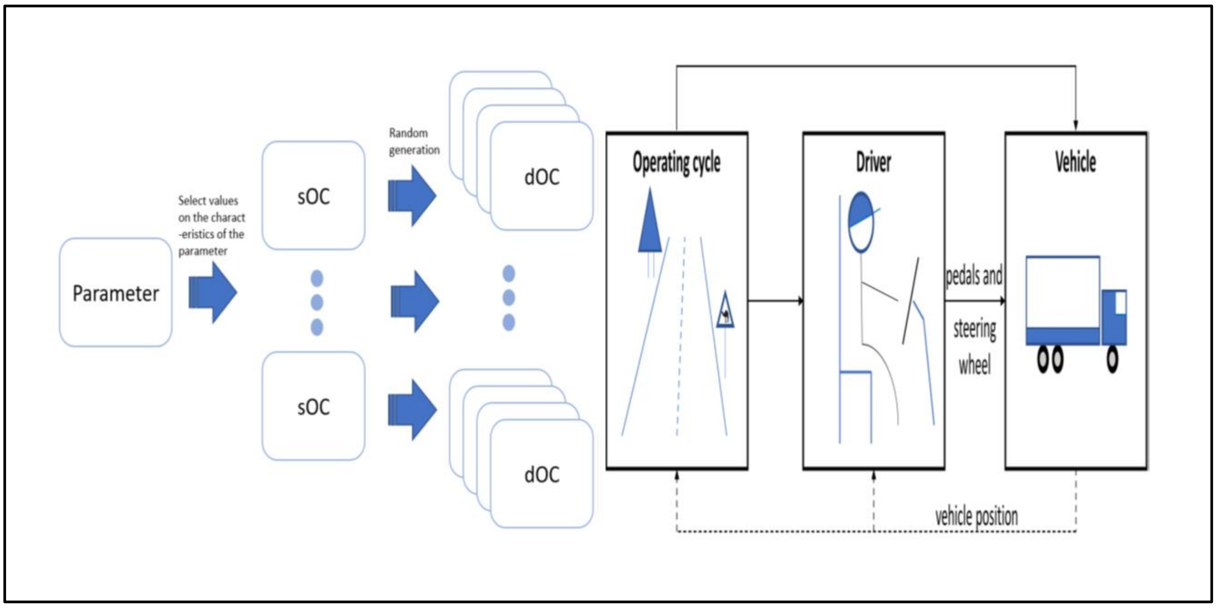

Figure 1: Generating dOCs from sOCs model (a) [9] Forward-facing modeling structure (b) [10]

When it comes to vehicle operation, various vehicle topologies and configurations may perform differently depending on environmental conditions and transport mission. Manufacturers and subsystem suppliers are being pushed to create Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) ideas with higher degrees of electrification and energy storage inside the powertrain due to legislative restrictions [11]. Each topology has its advantage depending on the geography where it operates and also on the kind of mission it is up to [12].

The amount of energy saved by a well-optimized drivetrain is mostly determined by the vehicle propulsion system and the duty cycle [13]. This thesis focuses on analyzing the various powertrain parameters that affect energy consumption, which is the most crucial step during drivetrain design (for example, battery weight, motor efficiencies, or varying engine operating points; the reason for this choice is explained in the Powertrain parameters section). Thereby one can predict and try to optimize the crucial factors. Since energy efficiency has been assessed by simulation results, this eventually leads to cost reduction and can be useful in developing an optimal vehicle design.

Implementation has to be done in the “VehProp” environment, which is a simulation model library for vehicle operation in Simulink created by Chalmers and it is open-source.

1.2 Problem definition

There is no distinct parameter that entirely affects heavy vehicle range. Depending upon the route, driving style, vehicle propulsion, etc. there are plenty of factors that may have an impact on energy consumption. Previous work was focused more on environmental factors affecting the range and energy consumption and was mainly limited to an electric vehicle.

Analysis of various major parameters in powertrain configuration e.g., battery weight, motor efficiencies, regenerative braking, etc. will give better insight into power consumption. Considering battery storage extra features, such as the battery management system, the cooling, and safety system, etc. will add up weight and influence the energy utilization. Similarly, motor factors like copper losses, hysteresis, and eddy current losses are the ones resulting in efficiency losses which in turn rises the energy usage. At least two distinct vehicle drivetrain characteristics and their impact on the OC should be the subject of this study. The operating cycle must be considered while designing a vehicle or selecting a vehicle for a specific mode of transportation.

Investigating should be carried out on environmental parameters that are affecting the energy utilization during vehicle operation. Further, a relationship needs to be established between the powertrain parameter and the environmental parameter for a better prediction of energy usage.

1.3 Problem objective

The objective is to implement and evaluate energy consumption for two different heavy vehicles powertrain (BEV & ICE) parameters (like payload, battery size, motor size, etc.) by utilizing the environmental models incorporated in the OC format. Research on the sensitivity of various factors on BEV powertrain configuration and their influence on energy consumption will be the primary objective.

The secondary objective is to extend the model work and analyze the ICE topology parameters affecting energy consumption.

1.4 Research question

A research question can be devised that acts as a question to summarize the main goal of this project and helps in formulating the project conclusion. These were thoroughly analyzed and the solutions to these questions along with sufficient activities build the key elements needed to achieve the objectives. The research questions topics that were formulated are summarized below:

1. How do different environmental factors (like topography, curviness, etc.) impact energy consumption?
2. Which external factor should be examined, how does it affects vehicle parameters energy usage, and why?

1.5 Limitations

Limitations are necessary to determine the overall scope of the project along with a few assumptions. The limitations and assumptions identified were as follows:

1. The focus will be on studying the model complexity of the existing vehicle topologies, not on OC or driver modeling/driver influence.
2. The model only considers longitudinal dynamics.
3. Required and most influential OC parameters will only be considered as input.
4. Modeling will strictly be restricted to the MATLAB/Simulink in VehProp.
5. There won't be any physical testing of a vehicle, which is out of scope for this project.
6. Assumption will be carried out in case any parameter values aren't available.

1.6 Approach: Waterfall model

The reason behind choosing the 'waterfall model' is because of the advantages that this model has to offer. Some of the advantages are that this is a short-term project with low-risk modeling and if there are any errors, the Environment models can be recalled. Hence, according to this model, the project was broken down into activities that resulted in a deliverable. Different stages of this project can be found in Figure 2.

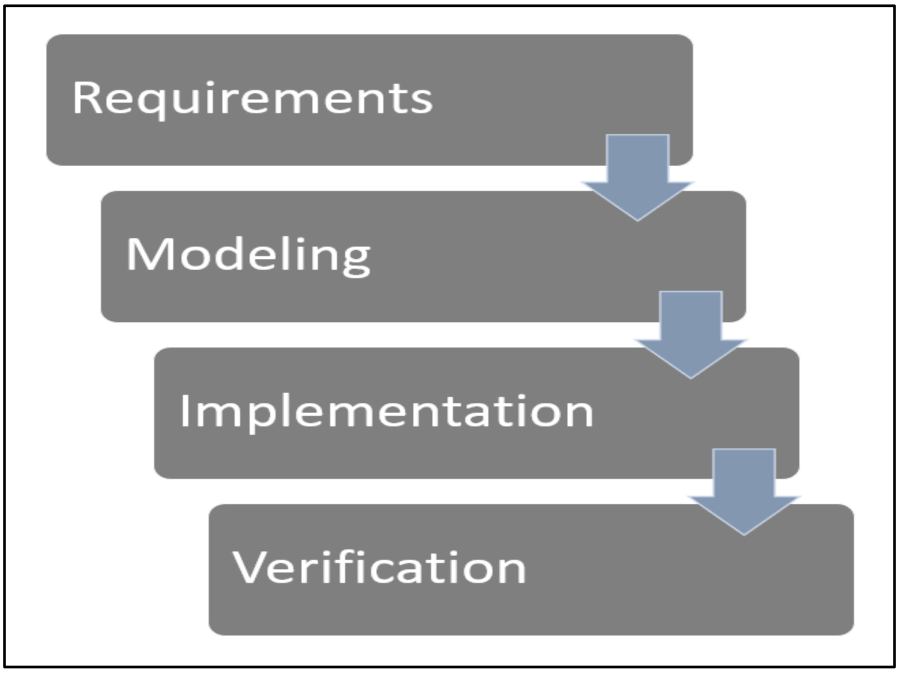

Figure 2: Different stages of the project based on a waterfall model

1.6.1 Requirements

In this stage, the requirements from the project client were analyzed and processed. The problem definition and project objectives are a result of this phase. Some of the requirements are:

1. Try to model environmental parameters using previous knowledge and experience to predict the most influential one.
2. Extend the scope of the project by combining different environmental parameters for multiple test cases to evaluate total energy consumption.

1.6.2 Modeling

In this stage, the previously mentioned requirements and project objectives were studied, and the needed software is chosen. In addition, to come up with a start, a literature survey was performed. With the knowledge gained from this study, an environmental model will be developed. A decision will be made if any further changes to powertrain models are needed.

1.6.3 Implementation

During this stage, the developed environmental model will be given as input and simulated for various powertrain parameters. Later energy consumption for each drivetrain parameter will be carefully analyzed. Overall, an estimated relation will be developed to find out which external parameters are most influential toward energy utilization.

1.6.4 Verification

One way of verifying is by using a hypothesis test because both environmental models and simulation results obtained will be based on mathematical methods. Assumption of additivity will be carried out to test the hypothesis for different contributions, e.g, the energy contributions from topography can be added to the contribution from the curves, and so on. Finally, results from the available individual data were analyzed and compared with the combined model data.

1.6.5 Outline of the thesis report

From the above-mentioned approaches, this report has been divided into certain chapters that explain how this project unfolds. Each chapter explains in detail the approach strategies and the reason behind this approach. In the end, the appendix section will give a much more comprehensive review of certain aspects of the project which require more explanation.

This report is preceded by the abstract at the beginning and later ends with the appendix and is dissected into the following chapters:

1. Introduction
2. Literature survey
3. Methodology
4. Results and discussion
5. Verification
6. Conclusion
7. Future work

1.7 Authors contribution

The author's contribution to the COVER research is to determine the relationship between environmental factors and energy consumption, as well as to determine which parameter has the greatest impact on energy usage. Further to see if each individual environment parameter that contributes to energy consumption can be separated from overall energy consumption while maintaining additivity.

To achieve the above-mentioned tasks the author developed two environmental models using the OC format. Further, the author was responsible for modeling environmental properties, analytical investigation, and simulation. It is worth emphasizing that Chalmers has provided the vehicle model. Significant improvements to battery electric vehicles were made before simulation results were generated. Further, changes to the ICE topology were not required.

LITERATURE SURVEY

A literature survey is the most basic and important step which has to be done to get an in-depth understanding of the project and what steps have to be taken next. This activity behaves as a bridge between our knowledge and the recent research that has been accomplished in the OC format. The important research survey which was required for the project is listed down below accordingly:

2.1 Operating Cycle

There are many uncertainties while using the driving cycle, few of them are already discussed in the previous sections. A clear flaw is the absence of certain physical features that have a direct impact on the vehicle such as topography, road curvature, and road roughness are a few examples [14], [15], [16]. This chapter will discuss how OC overcomes this with a few of its parameters.

As discussed in the background section, the three levels of description will be introduced with each having its own representation principle. The complete operating cycle section's terminology, figures, and ideas are all taken from Pettersson's and Romano's study [8], [17].

All three levels and their purposes are briefly covered in this section. A detailed way of building a physical world for external factors (such as topography and curviness) using different mathematical techniques are explained in the Environmental methodology section.

2.1.1 A high-level description

It is called a bird's eye view; the purpose is to provide an overview of entire transport applications, without going deeply into details. One such classification is Global Transport Application (GTA) which is used by Volvo trucks to develop products [18]. GTA is built around three main categories as mentioned in Table 1. This kind of classification is needed because it is not practical to develop products for a single user or a particular drive cycle.

Table 1: Parameters in GTA

Transport mission	Vehicle utilization	Operating environment
Vehicle type	Operating cycle	Road condition
Body and load handling equipment	Speed changes	Road type
Gross combination weight	Maneuvering	Topography
	Yearly usage	Altitude
	Diesel fuel sulfur level	Ambient temperature
		Curve density
		Dirt concentration
		Dust concentration
		Bug concentration
		Rolling resistance
		Coefficient of traction
		Load-bearing capacity of the ground

2.1.2 A mid-level description

If an operating environment is known and data is accessible, more information such as energy usage and power consumption may be retrieved; however, gathering data is not economical. What if there was a way to create a physical environment (road slope, road curvature, speed change, and so on) by applying a mathematical approach to generate all the necessary data? One such method is the stochastic process or stochastic operating cycle (sOC). Will take a closer look at how this can be achieved.

The sOC uses three main mathematical approaches: autoregressive processes, Markov processes, and Poisson processes to generate required data. Using these mathematical methods sOC results in numerous unique data, where events and variations occur by default.

The physical environment for the road properties needed to build using a mathematical approach is summarized in Table 2. The third column represents whether the generated data is continuous or discrete (event-based). The n represents number of states particularly speed signs and ground type that occurs along a certain route. The last column tells the number of mathematical parameters needed to fully model the physical environment for the road properties.

For example, this project looks at topography and curviness models. Table 2 tells that two mathematical parameters are needed to model topography, they are variance (σ_{Y}) and hill length (L_{h}). Similarly, six mathematical parameters, namely the intensity of curves (λ_{C}), log-normal mean radius (μ_{C}), log-normal standard deviation (σ_{C}), expectation value of curve length (μ_{L}), standard deviation of curve length (σ_L), and minimum turn radius (r_{turn}) are required to model curviness, these statistical parameters are responsible for building the physical world for topography and curviness. The correlation between these statistical parameters with the physical world is explored in the Environmental section.

Table 2: A summary of the models in the sOC format

Road property	Model type	No. of states	No. of parameters
Stop signs	Marked Poisson	Continuous	3
Give way signs	Marked Poisson	Continuous	5
Traffic lights	Marked Poisson	Continuous	5
Speed bumps	Marked Poisson	Continuous	3
Speed signs	Markov process	n_s	n_s^2
Ground-type	Markov process	n_g	$n_g(n_g + 1)$
Topography	Gaussian AR(1)	Continuous	2
Curviness	Marked Poisson	Continuous	6
Road roughness	Laplace AR(1)	Continuous	2

A hierarchical structure is necessary to categorize road types (urban, rural, highway). Depending on the location, several guidelines are used to build roads. For instance, a city street will have a lower speed limit, severe turns, and frequent stops and a highway segment will have a higher speed limit, shallow curves, and fewer stops. The road type becomes a primary model, while all other properties (like speed bumps, speed signs, etc.) will become secondary models as shown in Figure 3. This results in a selection of the statistical parameters in such a way that, on highways number of shallow curves and lower traffic lights will be generated, and in urban regions vice-versa. As a result, the hierarchical structure aids in different parameter values based on the road types. Similarly, weather and traffic classification are also done in sOC models.

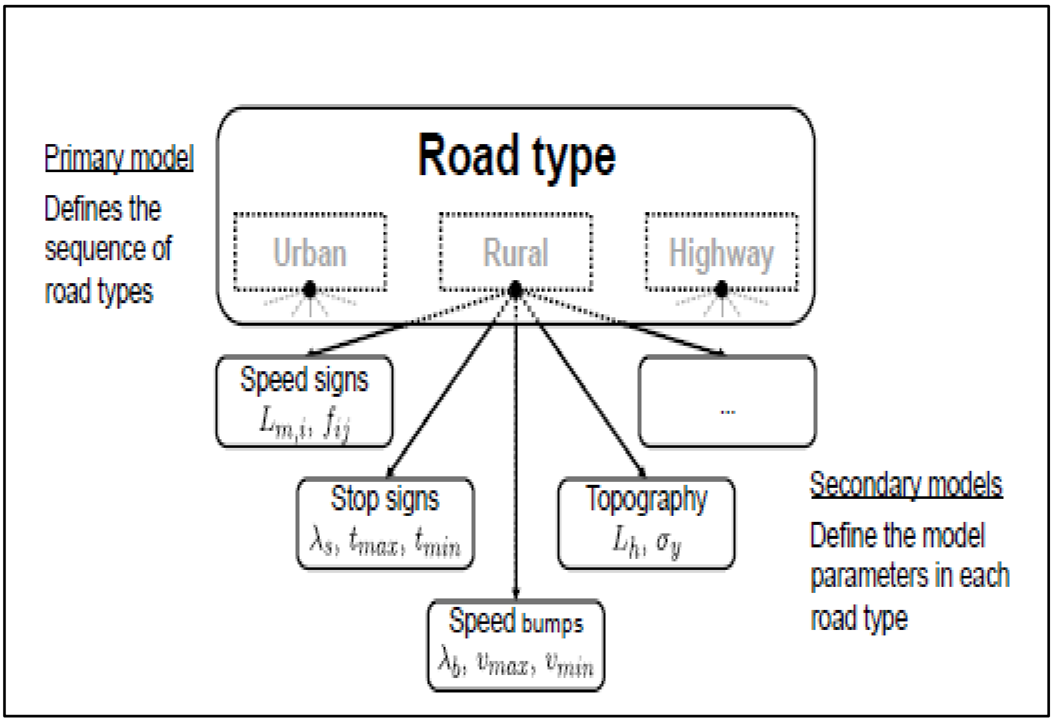

Figure 3: A graphical view of the hierarchical structure

2.1.3 A low-level description

The sOC will generate a bunch of data and each data is represented in the form of a deterministic operating cycle (dOC). Therefore, dOCs of generated data act as a road profile for an associated environmental model. It is a very precise description intended to accurately depict the physics of the world in a simulation environment.

Each data in dOCs will act as a sequence of ordered pairs $\{\xi_k, p_k\}$. Here ξ represents position or time and p represents physical quantity. For example, if a data is generated for a speed sign model then ξ_k represents the location or position of the speed sign board and p_k represents the number of times the vehicle's speed changes as it moves through its operational environment.

As stated in the background section, dOC will be fed in as an input to the driver and vehicle subsystems which can be seen in Figure 1. The dOC format is defined as a collection of sets:

$$OC = \{R, W, T, M\}$$

Where R is a set that contains road sequences, W is for the weather, T is for traffic, and M is for a mission. These are the four categories that are defined as sets that include the parameter sequences to officially formulate the dOC format.

2.2 Powertrain parameters

There are several powertrain characteristics that might have a significant impact on energy consumption. Sensitivity on powertrain parameters has been determined in this project based on the complexity considered in the “VehProp” model. The parameters that were taken into account are stated below.

2.2.1 Battery weight

Energy consumption per km driven is one of the criteria that can be easily determined based on the technical aspects of an electric vehicle. An increase in the range can be done by adding the number of battery cells which eventually led to an increase in battery weight. Extra features, such as the battery management system, the cooling, and safety system, and the assembly box for battery modules, also add to the weight of batteries [19]. A study on battery weight will give better insight into how the battery weight is affecting energy consumption.

2.2.2 Motor efficiency

Electric motors should be able to function in a wide torque and speed range in various applications, such as in automobiles. Efficiency mapping is used as a measuring tool to assess and compare the performance of EVs over their torque-speed plane. Since heavy vehicles demand a greater load to drive at higher speeds, machine efficiency will suffer [20]. A study will be conducted on different efficiencies.

2.2.3 Engine operating point

Engine efficiency varies dramatically based on the route, driving style, and other internal engine parameters, causing engine operating points to differ significantly from their ideal settings. To examine sensitivity analysis on engine operation settings, many test scenarios have been studied [21]. This thesis focuses on one of the test scenarios, by altering the engine's operating point.

METHODS - ENVIRONMENTAL MODELS

This project completely focuses on modeling road properties. The complete methodology section's terminology and ideas are all taken from Pettersson's and Romano's study [8], [17]. The OC helps to understand environmental models in a mathematical description.

3.1 Topography

From the generic equation of a longitudinal vehicle dynamics force, where the gradient of a slope is directly associated, it is of utmost importance to calculate the power required to overcome gradient resistance and the energy recovered from downhill. This is the reason to choose the topography from the road property for analysis.

Before diving into mathematical terminology, let us have a look at how topography in the real world is connected to these mathematical expressions. As topography is a change in altitude that provides us an understanding of how much the slope percentage of a hill varies and how long the hill is. In mathematical terms, a change in slope is known as variance (σ_{Y}) whereas, hill length is interpreted using the autoregression coefficient (ϕ_{Y}). Table 3 tells the relation between sOC parameter values for topography in the GTA classification. Higher the σ_{Y} value steeper the hill becomes.

Table 3:The relation between the sOC topography and the GTA class.

Amplitude	GTA Class
$\boldsymbol{\sigma_{\mathrm{Y}} < 1.29}$	Flat
$\boldsymbol{1.29 \leq \sigma_{\mathrm{Y}} < 2.58}$	Predominantly flat (PFLAT)
$\boldsymbol{2.58 \leq \sigma_{\mathrm{Y}} < 3.87}$	Hilly
$\boldsymbol{3.87 \leq \sigma_{\mathrm{Y}}}$	Very hilly

The term "topography" refers to slow changes in altitude, which describes in terms of a percentage road gradient. Let k be a partition segment on road, the road gradient $Y_k \epsilon \mathbb{R}$ is a random variable on each k. Topography is modeled by using the Gaussian Auto Regression first-order approach:

$$Y_k = \phi_{\mathrm{Y}} Y_{k-1} + e_k, \qquad e_k \sim N(0, \sigma_e^2) \tag{1}$$

Here ϕ_{Y} is the autoregression parameter and is interpreted as a hill length L_{h}. The route is divided into separate chunks, each with a length $L_{\mathrm{s}} \ll L_{\mathrm{tot}}$. The hill length is the average difference between two peaks or valleys, and it may be regarded as the topography's main wavelength:

$$L_{\mathrm{h}} = \frac{4\pi}{\pi - 2\arcsin(\phi_{\mathrm{Y}})} L_{\mathrm{s}} \tag{2}$$

Instead of an error amplitude (σ_e), topography amplitude can be stated as:

$$\sigma_{\mathrm{Y}}^2 = \frac{\sigma_e^2}{1 - {\phi_Y}^2} \tag{3}$$

L_{h} and σ_{Y} are the parameters which are required for the topographical model to be parametrized.

The topography in the dOC format is specified by altitude (z_k) rather than road grade as sOC produces data in gradient form. Hence conversion is a necessity:

$$z_{k+1} = z_k + \frac{y_k}{100} L_s = \frac{L_s}{100} \sum_{i=0}^{k} y_i + z_0 \tag{4}$$

Here y_k is a piecewise constant function, hence altitude will be a piecewise linear function.

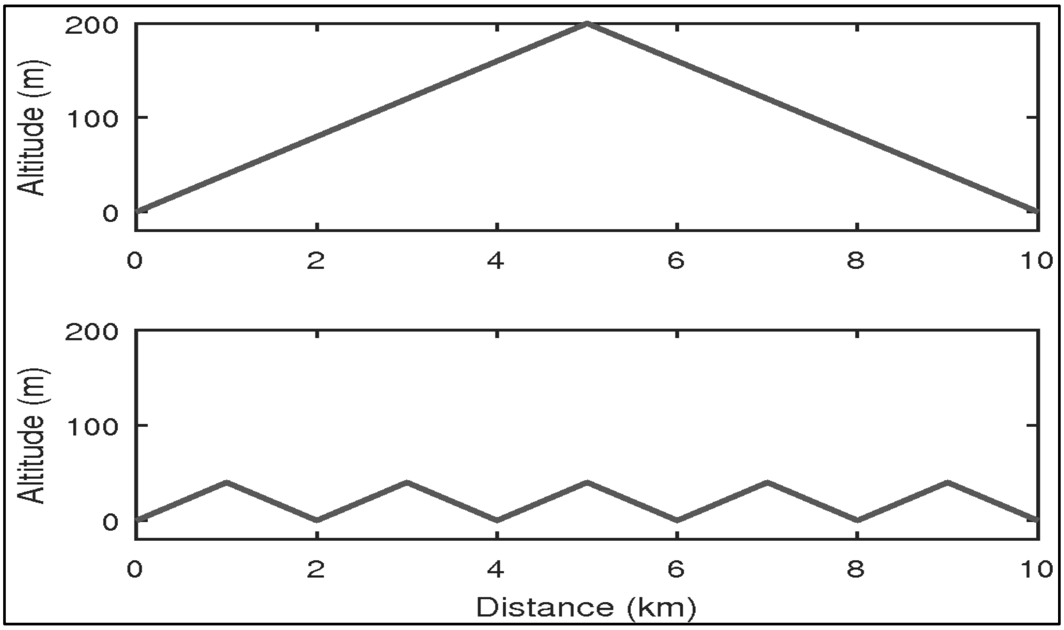

Figure 4: Topographies that have the same GTA-class (PFLAT), but different hill lengths

Figure 4 shows two examples of topographies that have the same GTA-class (PFLAT) but display distinctive characteristics. In the top plot, the hill length $L_{\mathrm{h}} = 10\,\mathrm{km}$, in the bottom one $L_{\mathrm{h}} = 2\,\mathrm{km}$. Multiple topography may be modeled by combining different variance (slope) and hill length parameter combinations.

Figure 5 illustrates different levels of representation in OC that will be used to construct topography. The number of dOCs or roads generated is a trade-off between the simulation duration and the energy consumption outcome. The number of dOCs required to forecast the optimum energy patterns, as well as different combinations (slope variance and hill length), are explained in detail in the Result section.

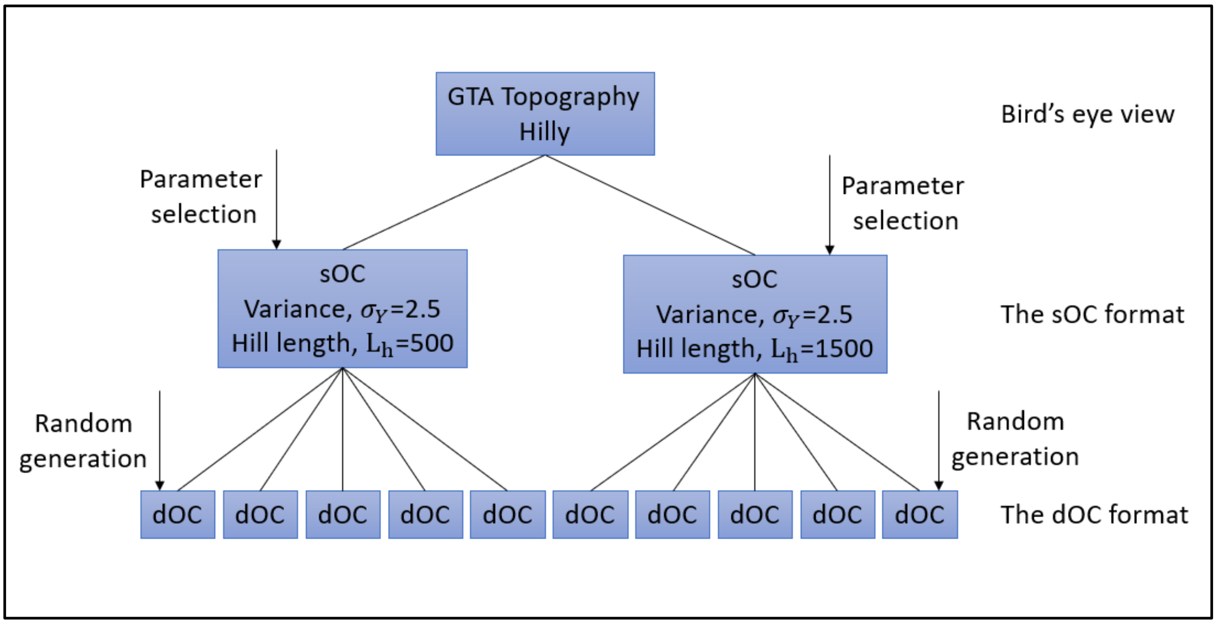

Figure 5: A view of the relations between the different levels of representation

3.2 Curviness

If the curves generated are too narrow and frequent, then this results in deceleration and acceleration of a vehicle which in turn utilizes more energy. Due to this reason, a curviness model has been included in the description.

Let us now look at how road curvature in the real world is connected to these mathematical expressions. As known curviness refers to uneven bends in roadways that cause a vehicle to shift direction in a graduated manner. While developing the curvature model, one should consider how steep and long the curves are to represent the real world. In mathematical terms, the steepness of the curve is modeled using two statistical parameters; log-normal mean radius (μ_C) and log-normal standard deviation (σ_C).

Whereas, the length of a curve is modeled using the expectation value of curve length (μ_{L}), and standard deviation of curve length (σ_{L}). In addition, two other parameters are taken into account: the intensity of curves (λ_{C}), which is the number of curves generated per unit length, and the minimum radius of turn (r_{turn}), which is technically not a statistical measure but rather an inherent property of the road type in which roads are built with a lower bounded radius. Figure 6 shows a glimpse of how these relationships help in building the road curvature along a given route.

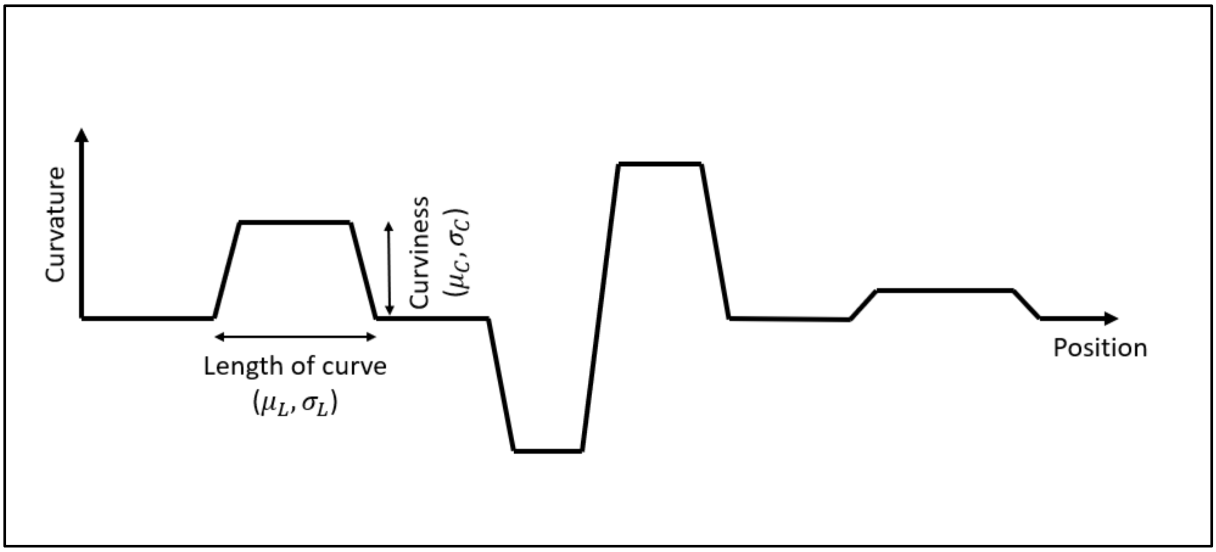

Figure 6: Relation between curvature, a continuous function of position, and curviness

The road curvature is a line that deviates from the horizontal geometry of a road in a smooth, continuous fashion. Although it is a continuous function of location, it is proposed that curves be seen as an independent events having a position X, curvature C, and length L.

The locations of curves $\{X_k\}$ are modeled using a Poisson process and a sequence of random variables. The number of curves per unit of length is measured by its intensity λ_C,

$$X_{k+1} - X_k \sim \mathrm{Exp}(\lambda_{\mathrm{C}}) \tag{5}$$

The curvature C is developed by the modified log-normal distribution;

$$R' = {}^{1}\!/_{C} - r_{\mathrm{turn}} \quad \ln R' \sim N(\mu_{\mathrm{C}}, \sigma_{\mathrm{C}}) \tag{6}$$

Where μ_{c}, σ_{c}, r_{turn}, R' and C are defined as log mean, log standard, a radius of turn with a lower bounded radius, radius of the curve, and curvature.

The curve length L will be modeled using a log-normal distribution:

$$\ln L \sim N(\mu_{\mathrm{L}}, \sigma_{\mathrm{L}}) \tag{7}$$

These six parameters λ_{C}, μ_{C}, σ_C, r_{turn}, μ_{L} and σ_{L} fully parametrize the curviness model.

The expected number n'_C of curves along the route whose curvature exceeds a minimal threshold k_{min} (0.008 m^{-1}) may be computed as follows:

$$n'_C(\lambda_{\mathrm{C}}, k_{\mathrm{min}}, r_{\mathrm{turn}}, \mu_{\mathrm{C}}, \sigma_{\mathrm{C}}) = \frac{\lambda_{\mathrm{C}} L_{\mathrm{tot}}}{2}\left[1 + \mathrm{erf}\left(\frac{\ln\left(\frac{1}{k_{\mathrm{min}}} - r_{\mathrm{turn}}\right) - \mu_{\mathrm{C}}}{\sqrt{2}\sigma_{\mathrm{C}}}\right)\right] \tag{8}$$

In this thesis, out of six parameters λ_{C} and μ_{C} will be considered as a varying factor and the rest of the other parameters will be fixed. The reason for selecting these two factors is that past research has shown that they create higher variations in the expected number of curves than other parameters.

3.3 Legal speed

The primary focus of legal speed in this context is to maintain constant speed throughout the trip, irrespective of where the vehicle is operating. As a result, there is no need for variation. Hence, the generation of sOC models was not considered. If desired, the OC has an option to model the speed sign to change speeds based on sOC characteristics.

VEHICLE MODELING

The complete vehicle model was done using VehProp in MATLAB/Simulink environment for evaluating the longitudinal performance by Chalmers. The reader is referred to [22] for a detailed description of VehProp.

If a vehicle follows a longitudinal trajectory the governing equation of motion can be formulated as:

$$m\dot{v}_x = F_x - F_{\mathrm{grade}} - F_{\mathrm{roll}} - F_{\mathrm{air}}, \tag{9}$$

Where v_x is the longitudinal speed, F_x is the longitudinal force, F_{grade} is the longitudinal force needed to overcome road gradient, F_{roll} is the rolling resistance, F_{air} is the drag force. Accordingly, the requested power to drive the vehicle can be estimated by:

$$P_{\mathrm{drive}} = v_x(F_x - F_{\mathrm{grade}} - F_{\mathrm{roll}} - F_{\mathrm{air}}), \tag{10}$$

The total power to propel the vehicle that needs to be supplied will be:

$$P_{\mathrm{tot}} = P_{\mathrm{drive}} + P_{\mathrm{aux}} + P_{\mathrm{PTO}}. \tag{11}$$

Where, P_{aux} is the power needed to supply auxiliary components, P_{PTO} is the power take-off [8], [17].

The vehicle model for BEV used in the thesis was based on a modified version of both Iuri Barro’s work and Marcus Berg and Conny Ta's work [23], [9] whereas for ICE it was based on Erik Nordström's work [24]. In this project, battery, motor, and regenerative power parameters were updated accordingly to the companies requirements mentioned below:

1. The power required from the motor should be sufficient enough to overcome the OC parameters developed along the given route.
2. Battery mass should be updated according to the number of packs present.
3. Different operating points for motor efficiency should be defined.
4. Multiple regenerating capabilities should be included in the model.
5. The model took into account various engine operating points.

All the above requirements were fulfilled in this project to conduct a sensitivity analysis on the powertrain parameters.

It's worth noting that the BEV model has changed and evolved from project to project, whereas the ICE vehicle model has been validated. Though modeling is not part of this project, the majority of the effort is focused on determining the correlation between environmental parameters and energy consumption patterns. Trusting that the BEV vehicle model is reliable, and moving forward to produce outcomes.

Figure 7 illustrates a glimpse of how this project unfolds.

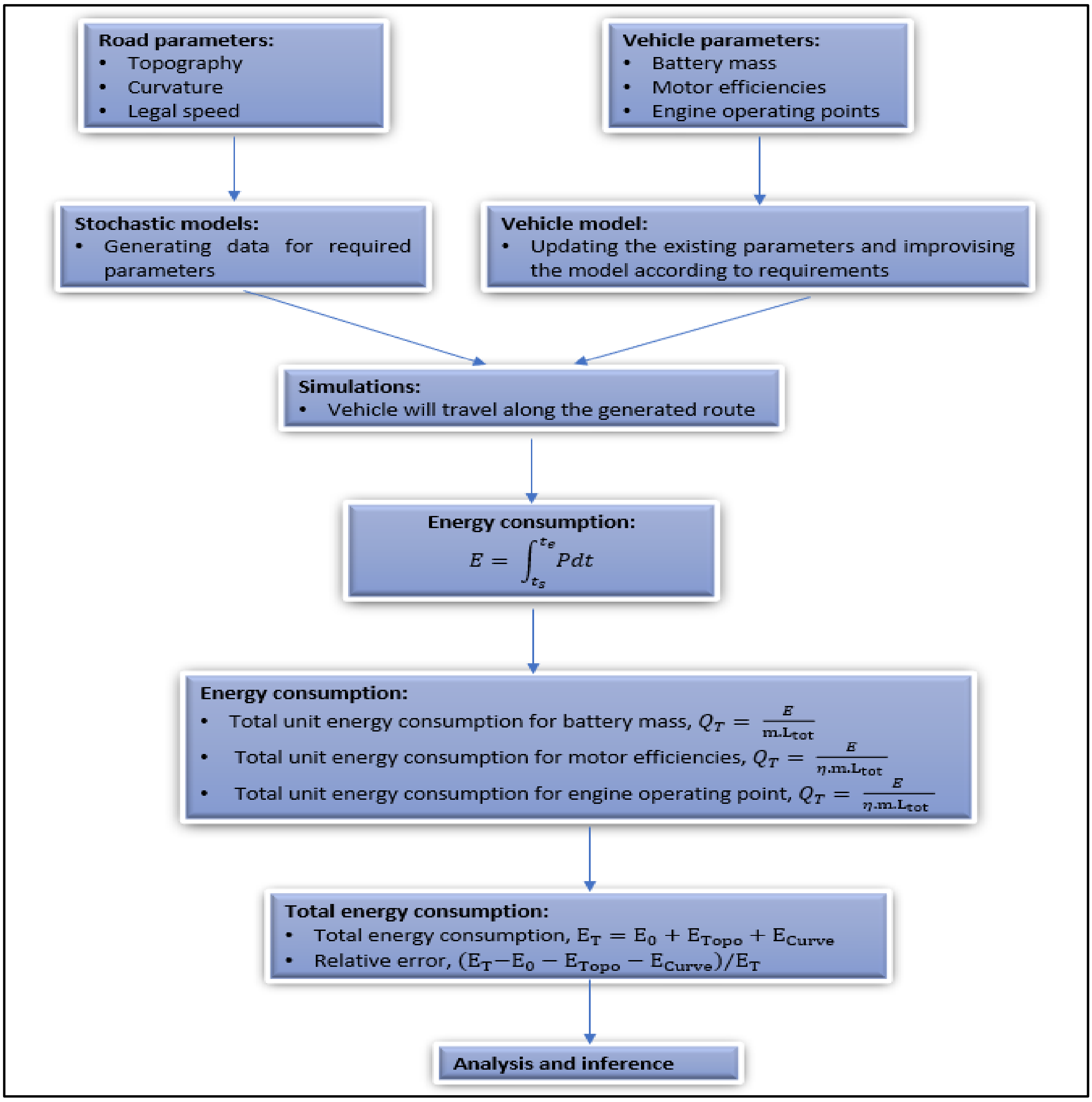

Figure 7: Flowchart of research and analysis methodology

RESULTS AND DISCUSSIONS

The stochastically generated road profiles should be interpreted in a statistical sense. As a result, simulating multiple road profiles is necessary to capture the mean effect of energy usage (and possibly a spread as well if interested). A basic case study was conducted on how the mean energy consumption was converging as a function of number of road profiles and the findings revealed that 50 dOCs (roads) were adequate for a chosen parameter or combination. For both curvature and topography, 9 different combinations of statistical parameters were investigated. During simulation, each set of combinations consisted of 50 dOCs. The data generated is for a distance of 50 kilometers. The next step is to reverse the sequences when it is half the distance (red dotted line) as illustrated in Figure 8. This guarantees that the altitude, and thus the gravitational potential energy, are the same at the beginning and end of the journey, allowing a fair comparison of energy consumption. The road's curvature, on the other hand, is anti-symmetric.

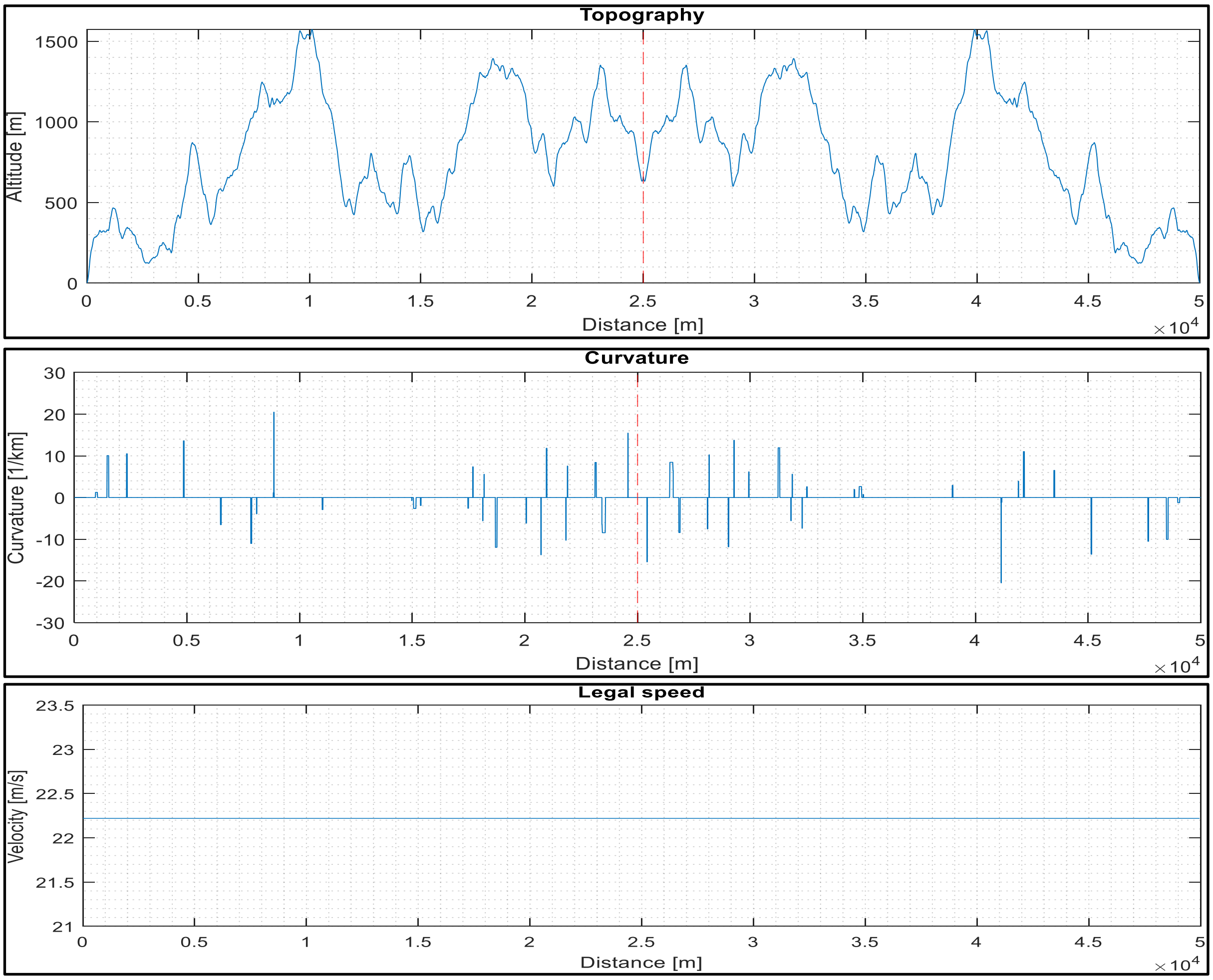

Figure 8: Topography and curvature generated from sOC for one of the road profile

The vehicle's overall energy intensity is proportional to its mass and distance traveled. A reference like this is defined as the total unit energy consumption of a vehicle:

$$Q_{\mathrm{T}} = \frac{E}{mL_{\mathrm{tot}}} \cdot \frac{1}{\eta} \tag{12}$$

Unlike the usually used conversion rate per 100 kilometers, this rate provides a far more objective assessment and comparison of the energy requirements.

5.1 Sensitivity on powertrain parameters for topography

As previously stated, the parameters considered for topography are listed in Table 4:

Table 4: Different parametric values considered for parameterizing the topography

Parameters:			
L_{h} [m]	500	1000	1500
σ_{Y} [%]	1.5	2.5	3.5

To capture various GTA classifications, the mentioned σ_{Y} values were chosen. A set of 450 roads are generated using these 2 parameter combinations. Since sOC creates random variation, the energy consumption spread will be wide when a vehicle travels along the generated path as shown in Figure 9. The median is shown by the center mark on each box, while the 25th and 75th percentiles are indicated by the bottom and top margins, respectively. The whiskers go all the way to the most extreme data points that aren't regarded as outliers, and the outliers are represented separately using the '+' marker sign.

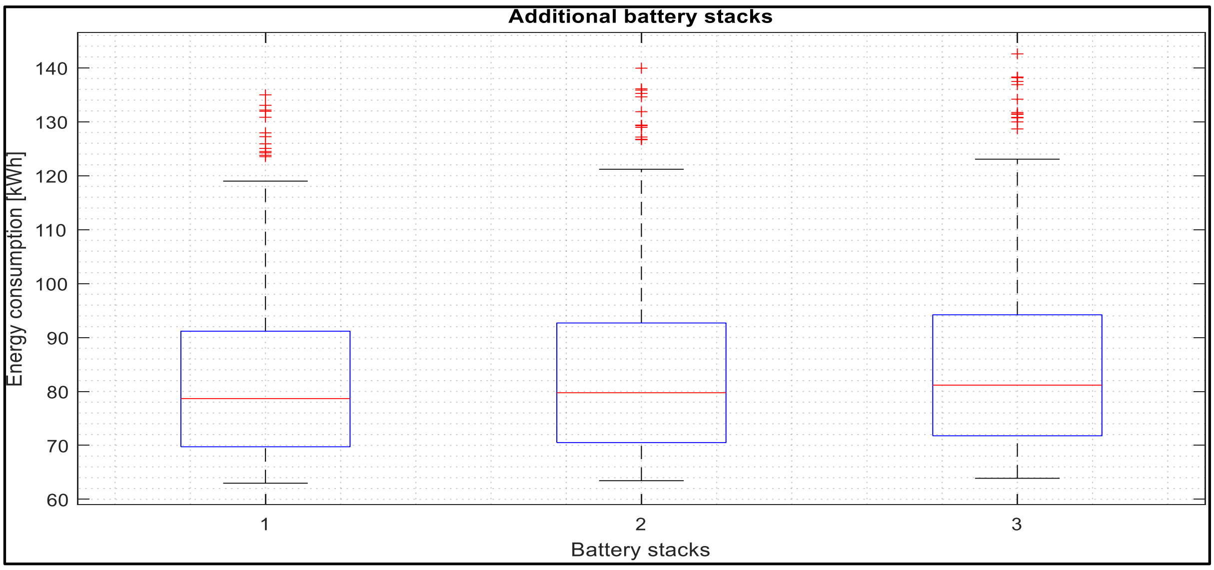

Figure 9: Energy consumption spread of 450 dOCs for 3 different battery stack sizes

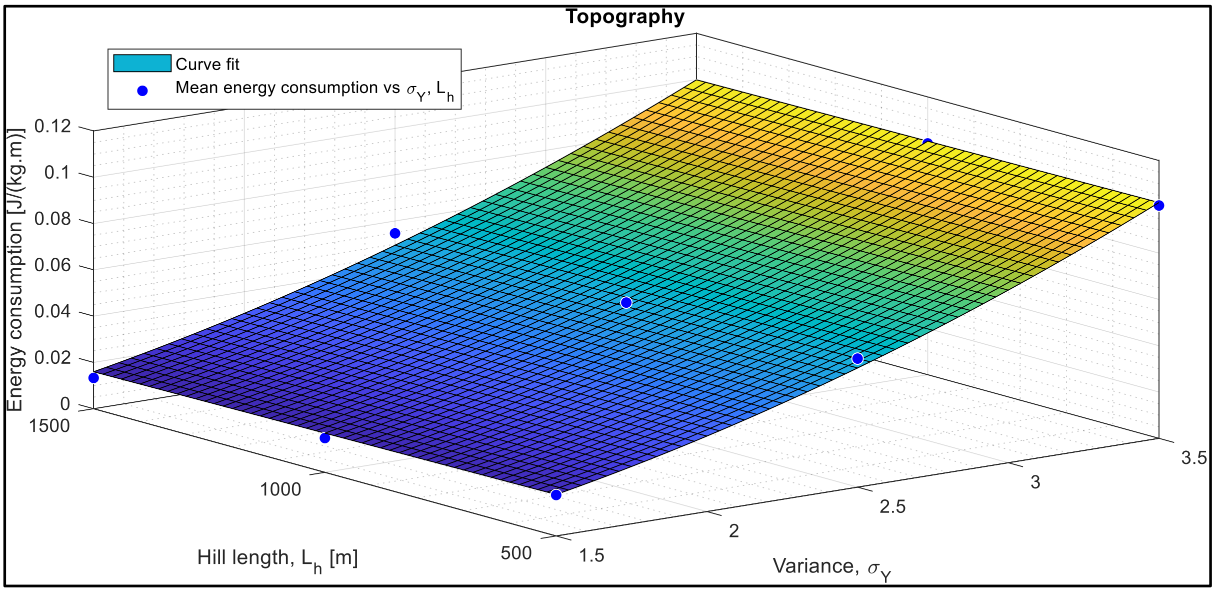

Figure 10: Unit energy consumption for BEV battery size along with the topography

For a better understanding of the results, a mean unit energy consumption value for each combination has been obtained. Results tend to increase in a quadratic trend as shown in Figure 10, Figure 11, and Figure 12 for both BEV and ICE topologies, for the relation between topographical statistical parameters with regards to different battery masses, motor efficiencies, and engine operating points.

The efficiency trade-offs across unit energy usage were then examined using curve fitting. Figure 10, Figure 11, and Figure 12 demonstrate a quadratic growth in energy consumption along the variance (slope); however, the hill length impact is fairly linear. As a result, it is possible to make educated guesses about the relationship (13). Let E be the energy consumption, where a and b are the coefficients. To avoid constant terms in the relation the energy consumption has been subtracted from the energy achieved from a flat road (E_0).

$$E_{\mathrm{Topo}}(\sigma_Y, L_{\mathrm{h}}) = a\sigma_Y^2 + bL_h \tag{13}$$

The marginal error for coefficients can be seen in Table 5 and Table 6 due to the condition that the driver must maintain a constant speed. Even though the speed necessary to overcome the slope stays constant, depending on which powertrain parameter is selected, there is a somewhat bigger variation in acceleration, causing the result to fluctuate.

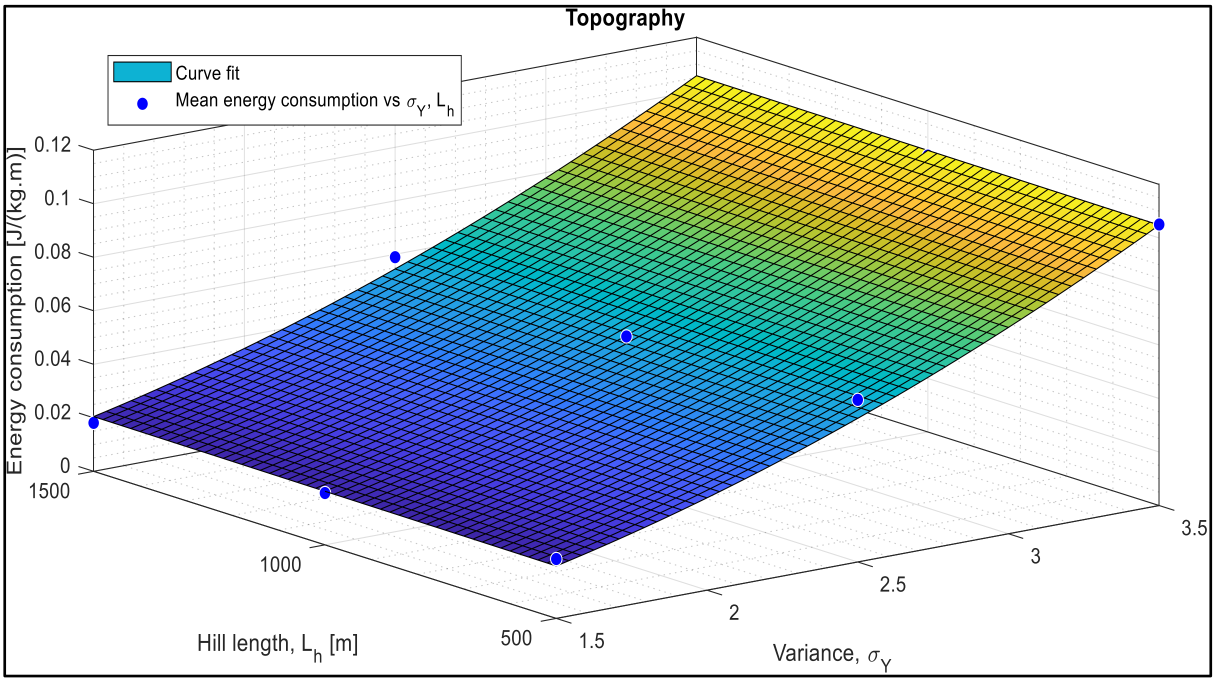

Figure 11: Unit energy consumption for BEV motor efficiencies along with the topography

In the OC, all other environmental parameters will be set to zero because topographical analysis for energy use will be the only point of focus. Coefficient results yielded for different battery pack masses for a 25-ton vehicle, a 35-ton vehicle, and motor efficiencies for a 25-ton vehicle are summarized in Table 5.

Table 5: Coefficients summarizing table for BEV along with the topography

Vehicle type 25-ton:	Coefficient a	Coefficient b	R^2
Battery stack-1	0.0084	1.946e-06	0.994
Battery stack-2	0.0086	1.723e-06	0.994
Battery stack-3	0.0083	5.28e-06	0.99
Vehicle type 35-ton:			
Battery stack-1	0.0089	2.345e-06	0.988
Battery stack-2	0.0094	1.574e-06	0.987
Battery stack-3	0.0094	6.683e-07	0.988
Vehicle type 25-ton:			
Motor efficiency-1	0.0091	3.47e-06	0.993
Motor efficiency-2	0.0088	3.45e-06	0.993
Motor efficiency-3	0.0083	1.385e-06	0.992
Average	0.0088	2.427e-06	

Coefficient results yielded for different engine operating points for a 25-ton vehicle are summarized in Table 6.

Table 6: Coefficients summarizing table for ICE along with the topography

Vehicle type 25-ton:	Coefficient a	Coefficient b	R^2
Optimal point-1	0.0073	1.093e-05	0.956
Optimal point-2	0.0071	1.554e-06	0.933
Optimal point-3	0.0074	1.458e-06	0.936
Average	0.0073	4.647e-06	

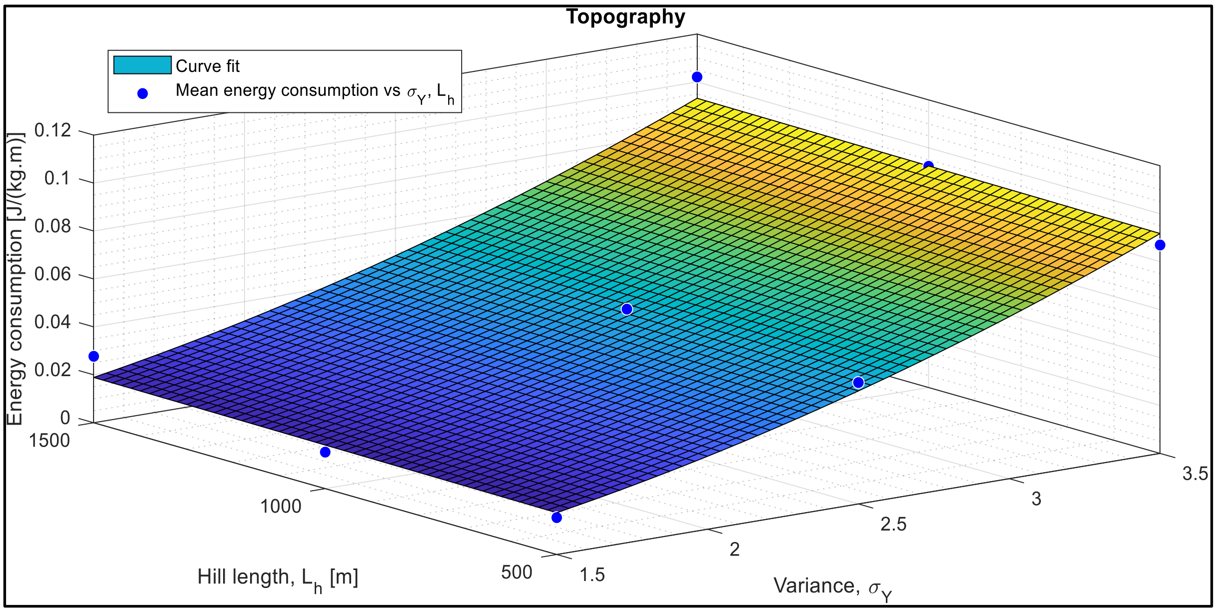

Figure 12: Unit energy consumption for ICE operating points along with the topography

The same conclusion can be drawn for the two distinct types of vehicle powertrain parameters able to produce similar energy consumption trends for topography parameters. Variance (slope) has the biggest influence on energy usage out of the two parameters which can be seen from all the above figures in this section. Since regenerative energy is disabled for BEV, the impact of a hill length has the same magnitude of outcomes for both topologies and is relatively linear.

When compared to ICE, BEV consumed more or about the same amount of energy, which cannot be true. This might be due to the complexity of the driver model and the potential for inaccuracies. Although the difference is minor, the BEV's energy usage should have been lesser than the ICE's.

5.2 Sensitivity on powertrain parameters for legal speed

The legal speed restriction for heavy trucks is taken into account for this project and evaluated vehicle movements along a flat road while keeping the rest of the environmental parameters at zero for the legal speed study.

$$E_0(L_{\text{speed}}) = a \tag{14}$$

Let E be the energy consumption, where a is the coefficient for legal speed. This study case demonstrates how a vehicle's energy consumption changes when it is subjected to forces induced by aerodynamic and rolling resistance as it travels along a straight road. This will be useful because any constants induced in topography and curviness relation will be subtracted from this legal speed flat road. It is even helpful for verification when comparing combined and individual energy contributions.

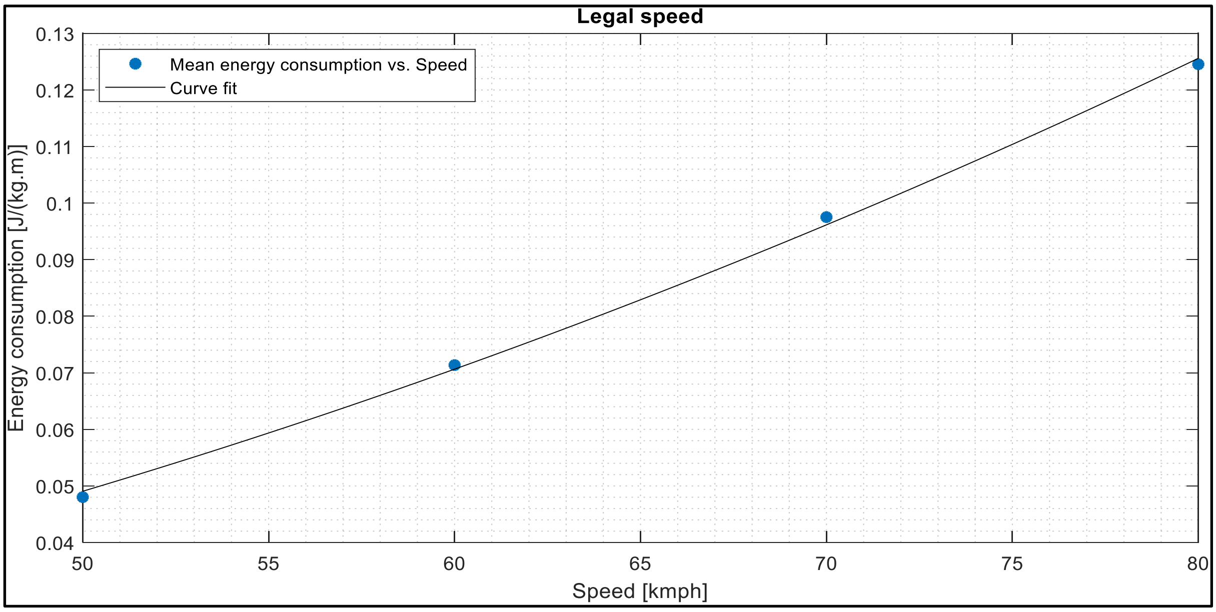

Figure 13: Unit energy consumption for BEV topology along with legal speed

The trend observed for the mean speed after using curve fit was quadratic, that at higher speeds coefficient of drag for the vehicle increases and is directly proportional to the square of its speed which can be seen in Figure 13. A similar trend can be observed for ICE topology Figure 14.

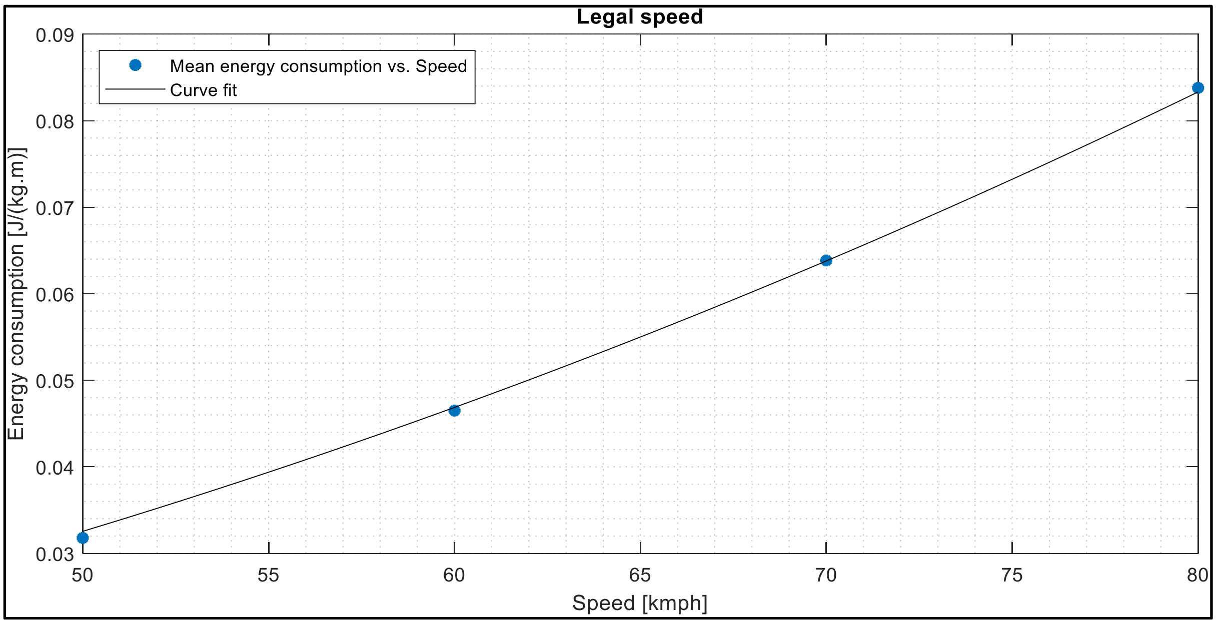

Figure 14: Unit energy consumption for ICE topology along with legal speed

5.3 Sensitivity on powertrain parameters for road curvature

The number of parameters required to parameterize curvature is six, as previously indicated. Varying all these parameters leads to a large factorial problem, therefore only those that have the greatest impact on energy consumption are examined. The first is the intensity of curvature, λ_C and the second is the Log-normal mean of radius μ_C. The values considered for these two are mentioned in Table 7. The remaining parameters are held to basic conditions, and the values that are listed in Table 8 considered here are according to previous studies.

Table 7: Varying parametric values considered for parameterizing the curvature

Parameters:			
$\boldsymbol{\lambda_C}$ **[km^{-1}]**	1	3	5
$\boldsymbol{\mu_C}$ **[ln(m)]**	1	3	5

Table 8: Constant parametric values considered for parameterizing the curvature

Parameters:	
$\boldsymbol{\sigma_C}$ **[ln(m)]**	1
$\boldsymbol{\mu_L}$ **[ln(m)]**	3.2
$\boldsymbol{\sigma_L}$ **[ln(m)]**	1
$\boldsymbol{r_{turn}}$ **[m]**	12.5

Figure 15 shows after using curve fitting that the energy consumption result for curvature shows a logarithmic trend that never reaches a maximum, but the rate of energy usage begins to level out at a certain point.

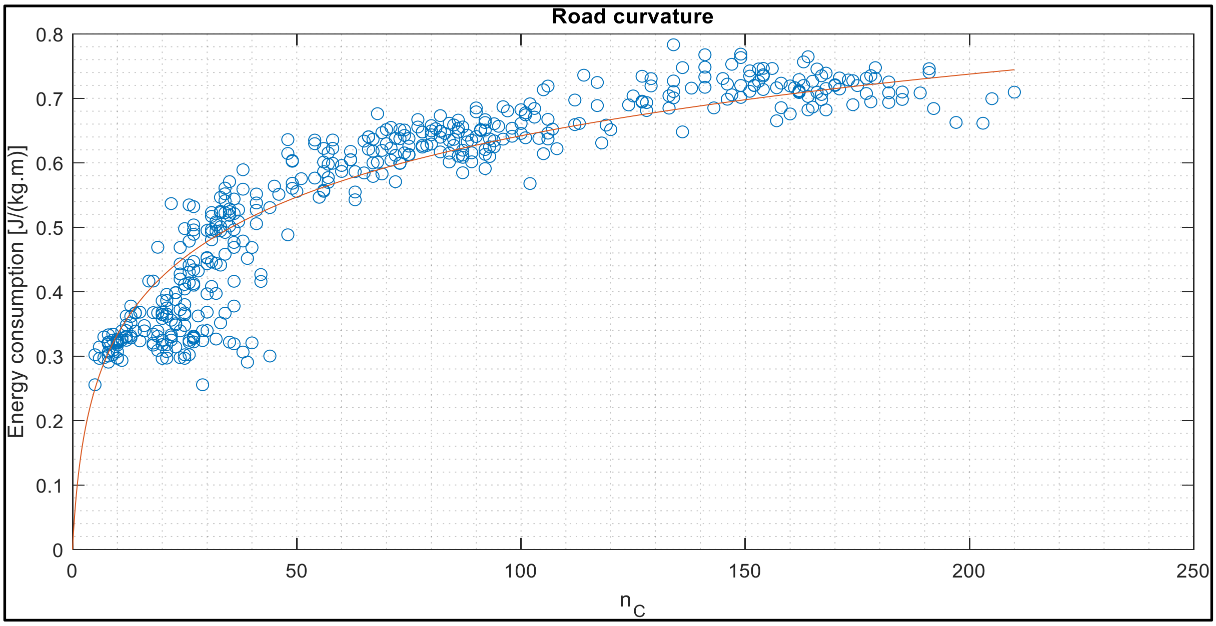

Figure 15: Unit energy consumption for BEV topology along the curvature

This made the prediction of energy trend relation to be logarithmic (15). Let E be the energy consumption, where a is the coefficient.

$$E_{\mathrm{Curv}}(n_C') = a\ln(n_C') \tag{15}$$

From Figure 15 it is evident that the unit energy consumption for curvature is relatively high compared to that of the other two environmental parameters. There are two explanations for this. The first is due to curve clustering this happens when the sharpest turns are clustered together rather than appearing independently. For example, driving on a four-way roundabout requires either one turn if you choose the first exit or three turns if you take the final exit. These are sharply curved bends that result in slowing vehicle speeds. The sequence of turns was regarded as independent in the curviness model. As a result, the driver must slow down three times, once for each curve, rather than only once for the entire cluster as on the real road.

The second reason is that the parameters of the curviness model are chosen in such a way that the number of curves generated along the path is high to cover all road types. This causes the vehicle to constantly accelerate and decelerate along the route which can be seen from the velocity profile in Figure 16.

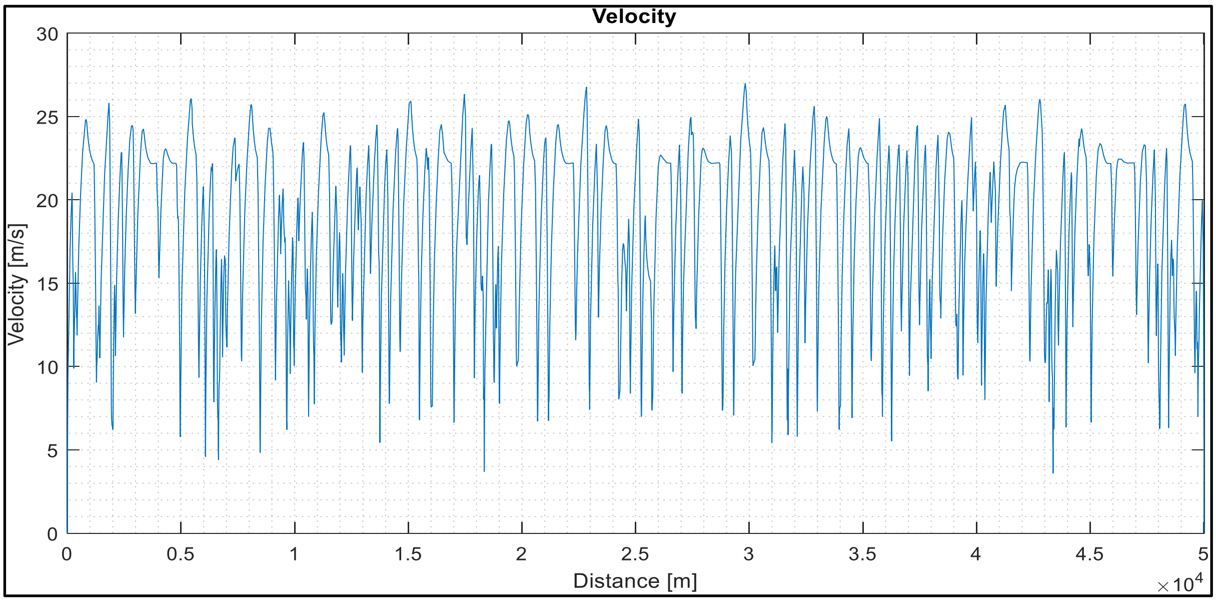

Figure 16: Velocity profile output for one of the sOCs of the curvature model

Coefficient results yielded for different battery pack masses, and motor efficiencies for a 25-ton vehicle are summarized in Table 9.

Table 9: Coefficients summarizing table for BEV along the curvature

Vehicle type 25-ton:	**Coefficient a**	R^2
Battery stack-1	0.139	0.859
Battery stack-2	0.148	0.839
Battery stack-3	0.151	0.839
Vehicle type 25-ton:		
Motor efficiency-1	0.146	0.87
Motor efficiency-2	0.156	0.847
Motor efficiency-3	0.151	0.84
Average	0.149	

For a 25-ton truck, the coefficients results for various engine operating conditions are summarized in Table 10.

Table 10:Coefficients summarizing table for ICE along the curvature

Vehicle type 25-ton:	**Coefficient a**	R^2
Optimal point-1	0.114	0.845
Optimal point-2	0.106	0.835
Optimal point-3	0.098	0.827
Average	0.106	

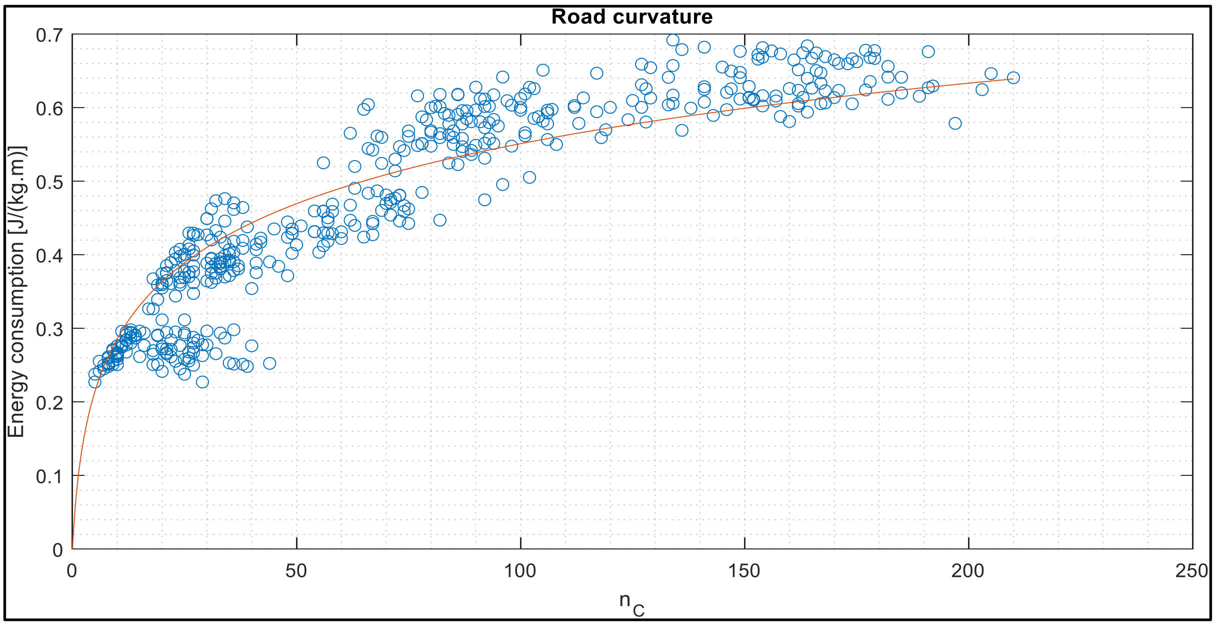

Figure 17: Unit energy consumption for ICE topology along the curvature

The data for ICE energy consumption in Figure 17 is lower than BEV clearly indicates that this should not be the case, as previously stated. Returning to the trend, the ICE architecture follows the same pattern as the BEV.

5.4 Sensitivity on the payload for topography

Regenerative energy is an important aspect of researching the topographical model as this thesis deals with BEV topology. The length of the slope had little impact on energy in the previous section. As a result, the best approach to investigate its impact will be to use it when a regenerative mode is enabled. To conduct this test, two different vehicles with the same number of battery stacks, battery power, and motor power to recover energy were used. The only varying parameter is its payload.

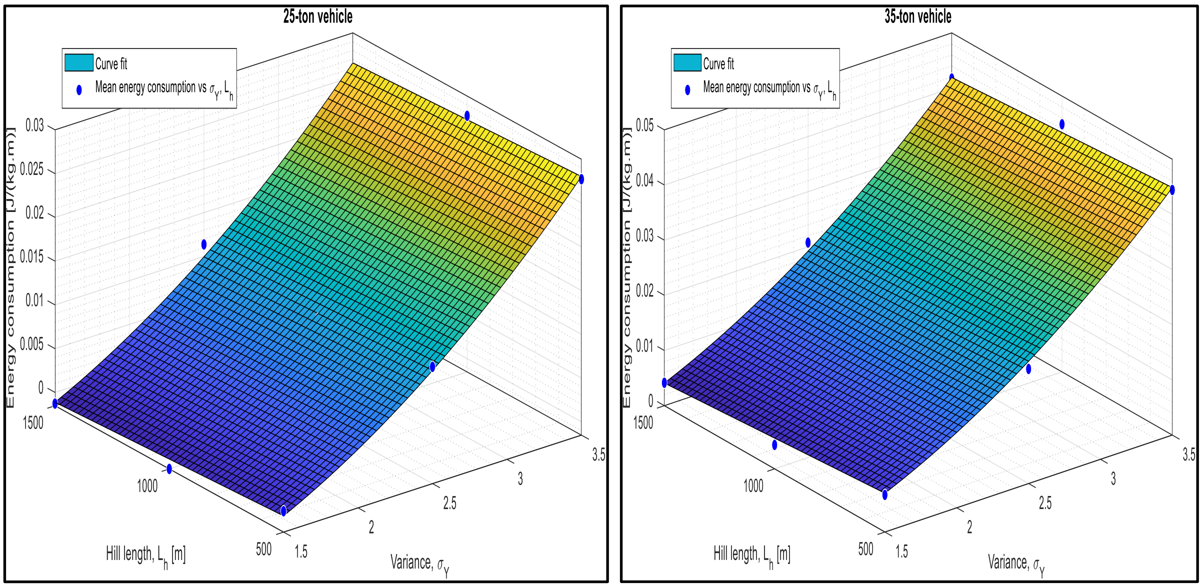

Figure 18: Unit energy consumption for BEV (regenerative) along with the topography

The 35-ton vehicle was able to extract roughly around 60% extra energy compared to that of the 25-ton vehicle. Therefore, it is evident that hill length has an impact on the energy recovery rate. The unit energy consumption rate for the two types of vehicles differs can be seen in Figure 18. This is due to the fact that both vehicles type are able to recapture distinct energy rates. Therefore, it is hard to predict coefficient values for the unit energy usage for BEV vehicles from the derived relation (13). The coefficients are summarized in Table 11.

Table 11: Coefficients summarizing table for BEV (regenerative) along with the topography

Vehicle type 25-ton:	**Coefficient a**	**Coefficient b**	R^2
	0.0026	4.614e-06	0.975
Vehicle type 35-ton:			
	0.0038	2.941e-06	0.995

But if the amount of energy recovery rate for different cargo vehicles in percentage is roughly known, one could simply multiply by this to get the average coefficient value. For example, as mentioned earlier that the energy recovery difference is actually 60% between 25 and 35-ton vehicles. Multiplying the mean energy values obtained for a 35-ton vehicle with 0.6 will result in a similar unit energy consumption which can be seen in Figure 19.

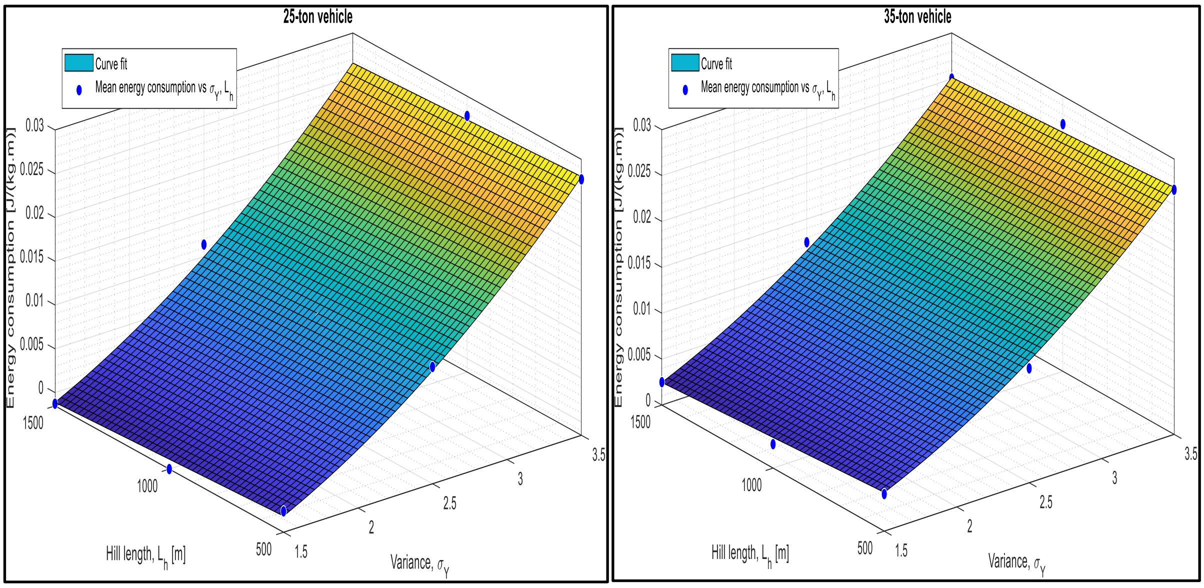

Figure 19: Normalized unit energy consumption for BEV (regenerative) along with the topography

The coefficients are summarized in Table 12. Now it will be much easier to plug in coefficient values to predict the energy consumption.

Table 12: Normalized coefficients summarizing table for BEV (regenerative) along with the topography

Vehicle type 25-ton:	**Coefficient a**	**Coefficient b**	R^2
	0.0026	4.614e-06	0.975
Vehicle type 35-ton:			
	0.0023	1.764e-06	0.995

VERIFICATION

The verification has been done using a hypothesis test because both environmental models and simulation results obtained are based on mathematical methods. The goal of testing the hypothesis using the environmental models and simulation results is to see how different individual environmental models influence energy usage. To check whether the assumption of additivity works for the energy contribution of the OC parameters, energy consumption from combined simulation should result in the same energy as if are adding different contributions individually, e.g, the energy contributions from topography, energy contribution from the curves, and so on. This is significant since it simplifies the approach by allowing analyses of each parameter in isolation. Since generating results for multiple combinations also requires a significant amount of simulation time, nine separate test cases were selected from the sOC parameters to get findings for diverse combinations (see Table 13). For each of these combinations, 50 dOCs are generated. For a fair energy consumption comparison, the same produced dOCs (roads) are provided as input for both combined and individual scenarios.

Table 13: Nine different test cases considered for total energy

σ_{Y}	L_{h}	λ_C	μ_{C}
1.5	500	1	1
2.5	500	1	3
3.5	500	1	5
1.5	1000	3	1
2.5	1000	3	3
3.5	1000	3	5
1.5	1500	5	1
2.5	1500	5	3
3.5	1500	5	5

The individual energy contribution can be combined to form the total energy consumption as stated,

$$E_{\mathrm{Tot}} = E_0 + E_{\mathrm{Topo}} + E_{\mathrm{Curv}} \tag{16}$$

Both the combined and individual simulations are kept to the same speed. Therefore, the vehicle is subjected to forces induced by aerodynamic and rolling resistance as it travels along the road. These factors enhance energy consumption and are always present in the basic case.

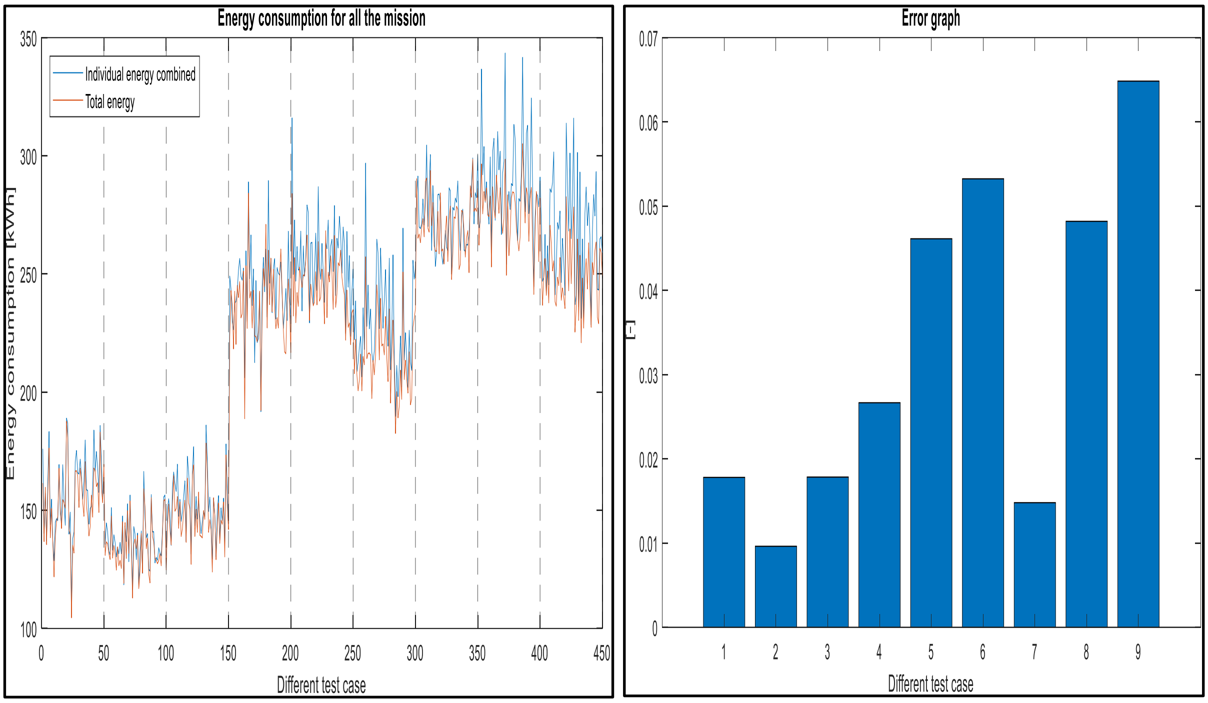

Figure 20: Total energy consumption vs individual energy consumption (a), the relative error between individual and combined energy consumption (b)

Figure 20(a) shows that total energy use is lower than individual usage, which is clearly not the situation in the real world. Because both topography and curvature models are built independently while simulating for a mixed situation, the possibility of an appearing steep slope with a severe curvature exists. This results in slowing down the vehicle and making it consume less energy, eventually leading to an error. The likelihood of these situations reoccurring increases as test cases with higher intensity (λ_C) and slope variance (σ_Y) is explored. Figure 20(b) illustrates how a situation like this can lead to a larger relative error difference in energy use.

In comparison to the rest of the trend in Figure 20(b), test case 2 appears odd. It is hard to say what caused the trend to have the least error, but one possibility is that both steep slope and curvature may not have occurred at the same time, resulting in a reduced inaccuracy.

The data in Figure 20(a) demonstrate that the energy contributions from the separate models were almost identical to the combined one, with a negligible error. It also demonstrates that energy contributions from the combined model can be separated to examine the individual environmental parameters. This might be advantageous in the long run for improving the vehicle for future generations based on which environmental factor influences more along a given route. Further, it can be useful to develop an estimator to better predict a vehicle's energy or the range.

CONCLUSION

The influence of environmental conditions on powertrain parameters was investigated in this thesis. Depending on the sOC settings used along a certain route, a rise in energy consumption patterns can be observed.

The whole outcome of establishing the relationship between the environmental and powertrain characteristics is determined by the vehicle model. While the ICE vehicle has been validated, the BEV has been evolving and upgrading in accordance with the project's goals. Because vehicle modeling is not part of this thesis, it was decided to trust and proceed based on the previous author's foundation. The study was focused on how they respond to external factors, rather than comparing the outcomes obtained for different topologies.

Among the two parameters examined for the topography model, variance (slope) has a bigger influence on energy usage than hill length. In reality, energy consumption for topography is highly dependent on both variance and hill length, but the circumstances for the driver model are considered such that the vehicle maintains its speed constant. As a result hill length shows less impact on energy usage as there is no need for deceleration or a need to change gears. Therefore variance (slope) plays a significant role in a quadratic rise in energy. The resulting trend was the same for both powertrain settings, with the exception of the BEV vehicle, as the regenerative mode is disabled. Further, the pattern stays similar when the regeneration mode is enabled. However, this time the hill length has a considerable influence on the energy recovery rate. This clearly shows that both factors have an impact on powertrain components.

When it comes to the curvature model, both the intensity and log mean radius (curviness) factors resulted in higher energy use. However, energy consumption grows in a logarithmic pattern for both topologies. It's difficult to predict when energy will level off; it can only happen if the number of curves formed for a given journey distance is indefinitely large, but this will never happen in practice. If the curve's precise numbers are known, an estimated sOC parameter will deliver the best-projected energy. In that case, the number of curves produced within a set of constraints along a given path will see the transition of a shift in curve trend from logarithmic to linear.

The goal of this thesis even aims to create an estimator that may predict energy usage based on sOC characteristics. This was not possible due to the time limit.

The conclusion that can be drawn from this project is that the objectives and the problem owner's requirements are satisfied. These include establishing the relationship between external factors and drivetrain parameters, updating the motor, battery, and regenerative properties of a vehicle according to the prerequisite, and also which sOC parameter influences the energy most.

FUTURE WORK

Through the recommendations, this project aims to put forward a road map for further work in research and development. Few of them are,

1. If the energy consumption of ICE and BEV topologies is to be compared, BEV model parameters must be updated in accordance with ICE. This project was solely focused on updating vehicle parameters, therefore the driver model should also be taken into consideration.
2. A more thorough investigation of the relation between powertrain characteristics and other environmental factors would be beneficial.
3. Developing an estimator; previous authors laid the groundwork that may be used to extend further.

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APPENDIX

1.1 Vehicle parameters

The vehicle parameters considered to generate results in this thesis are summarized in Table 14 and Table 15.

Table 14: BEV parameters (modified according to requirements)

BEV Specification	
Vehicle properties	**Settings (case1, 2 & 3)**
Electric motor power max	350 [kW]
Electric motor power min	-350 [kW]
Battery energy max	500 [kWh]
SOC max	0.9 [-]
SOC min	0.2 [-]
Rolling resistance coefficient	0.0056 [-]
Drag coefficient	0.7 [-]
Air density	1.29 [kgm^{-3}]
Vehicle frontal area	10 [m^2]
Wheel radius	0.49 [m]
Battery mass for additional stacks	500 [kg]
Varying motor efficiencies	0.8, 0.85, 0.9 [-]
Vehicle mass	25, 35 [ton]

Table 15: Different engine specs

ICE Specification		
Engine	**Max power (kW)**	**Max torque (Nm)**
D11K450	332	2150
D13K540	397	2600
D16K750	552	3550
Varying engine operating point	0.7, 0.8, 0.9 [-]	

The D13K540 engine specifications were used for this project. The vehicle mass and other general attributes are kept identical for both topologies to provide a fair assessment.