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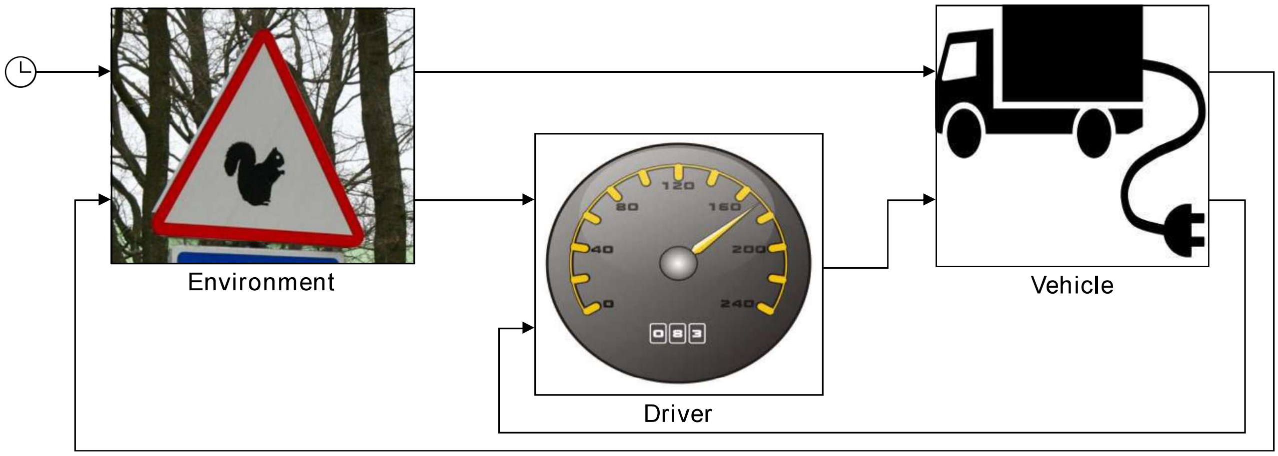

Voltage vs. Horsepower: Comparing Heavy Vehicle Performance through Simulation

TME180 Automotive Engineering Project 2024

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Abstract

Greenhouse gas emissions from the transportation sector are a major global concern, with the sector being one of the largest contributors. Improving energy efficiency within transportation systems is critical to mitigating these emissions. One promising solution is the introduction of Long Combination Vehicles (LCVs), which enhance logistical efficiency by increasing load-carrying capacity. By reducing the number of vehicles required to transport the same amount of cargo, LCVs contribute to lower emissions and promote more sustainable transportation.

This project investigates the energy consumption of a Battery Electric Vehicle (BEV) used for daily freight transport between Gothenburg Harbor and Viared. The LCV used for this operation is an A-double combination vehicle. The study employs a Forward Simulation modeling approach, accounting for environmental factors, driver behavior, and vehicle performance. It examines the energy cost and efficiency of this daily trip, as well as the vehicle's long-term operation over the course of a year. The analysis also explores how many trips can be completed and the total energy required for this operation.

Keywords: Long Combination Vehicle (LCV), Battery Electric Vehicle (BEV), Forward Simulation, Modeling

1 Introduction

This project investigates the energy consumption of a battery electric vehicle (BEV) configured as an A-double combination (i.e. a tractor pulling two semi-trailers, as illustrated in Fig. (1)). The focus is on the freight transport of customer goods between the Gothenburg harbor and Viared.

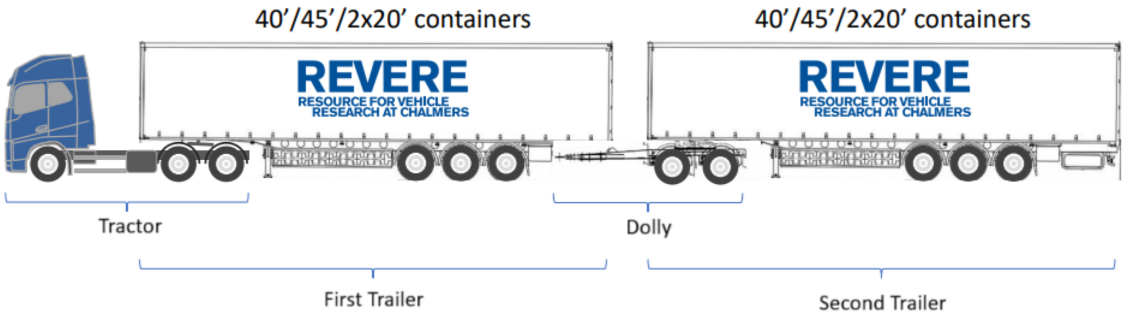

Figure 1: A-double vehicle combination

The energy consumption of the BEV tractor is analyzed using a *Forward Simulation* model developed in Simulink. The results are benchmarked against an average fuel consumption of Internal Combustion Engine (ICE) diesel trucks, used nowadays to carry out the same operation [1].

Additionally, this work addresses strategic questions relevant to prospective customers considering the adoption of BEVs:

1. Can a BEV complete the Viared-Gothenburg route daily, throughout the year?
2. Is a single charging station at Gothenburg Harbor sufficient, or is an additional station required at Viared?
3. How many deliveries can the driver complete each day?
4. What is the energy cost required by the BEV?

1.1 Background

The A-double combination is currently utilized in Sweden as part of the AutoFreight project, a collaborative initiative involving Volvo Technology AB., Chalmers, Borås Stad, VTI, GDL, VBG, Ellos, Kerry, Trafikverket, NetOnNet, ÅF Industry (AFRY), Fristads, Goodyear and Budbolaget. This vehicle configuration supports efficient freight transportation between the Gothenburg Harbor container depot and the Viared local distribution center, showing a 25% reduction in fuel consumption with respect to two single trailer trucks [1].

Reducing carbon dioxide emissions has emerged as both a legislative mandate and a strategic priority for stakeholders in the transportation sector. Stricter emissions regulations are being implemented globally, with further tightening anticipated by 2030. These regulations align with initiatives such as the European Union's Fit for 55 program and Sweden's national decarbonization goals [2].

In 2018, Sweden established a climate target to reduce CO_2 emissions from the transportation sector by 70% by 2030 compared to 2010 levels [3]. Concurrently, the European Union has mandated a 30% reduction in emissions from newly manufactured heavy vehicles by 2030 compared to 2019 [4]. These regulatory changes have intensified interest in the adoption of BEVs.

As of 2023, approximately 54,000 electric trucks were sold globally, representing a 35% increase from 2022. However, despite this growth, electric trucks account for only 1.2% of total truck sales. Significant challenges, including substantial upfront costs and insufficient infrastructure, continue to hinder the widespread adoption of heavy duty BEVs. Consequently, heavy vehicle manufacturers are often questioned by potential customers regarding the economic viability of electric trucks.

It is within this context that this project focuses on analyzing the energy consumption of a BEV to perform an operation currently handled by diesel trucks.

2 Literature Review

The use of BEVs for commercial transport and logistics have gained attention due to environmental benefits and possible reduction of operational costs compared to traditional ICEs. This literature review explores studies relevant to understanding the forward simulation model developed during the project to study the BEV's energy consumption.

2.1 Environment

Accurately representing the vehicle's operating environment is essential in a forward simulation model. The environment surrounding road transportation can be categorized into four subgroups: road, weather, traffic, and mission [5]. Each of these elements plays a crucial role in determining the fuel consumption, efficiency, and performance of a vehicle.

The road primarily affects vehicle dynamics and driving actions. Road factors such as topography, road surface conditions, curvature, and roughness significantly impact vehicle energy consumption and performance [5].

Weather conditions play a pivotal role in vehicle operations, particularly for electric vehicles (EVs), where they significantly impact battery performance and overall vehicle dynamics. Critical environmental factors such as temperature, wind, precipitation (including rain and snow), and humidity could be incorporated into simulation models to ensure accurate simulation results.

Low temperatures, for example, adversely affect battery efficiency, leading to a reduction in the driving range of EVs. Furthermore, adverse weather conditions influence vehicle dynamics by altering road surface characteristics. Snow or rain increases rolling resistance and decreases traction, which not only affects energy efficiency but also poses challenges to vehicle stability and safety [5].

Traffic density significantly impacts fuel consumption by determining how frequently a vehicle must stop, accelerate, or decelerate [5]. In highly congested scenarios, road traffic heavily influences the driver's choice of speed, which, in turn, affects both vehicle efficiency and fuel consumption [6].

Transport missions are often defined based on vehicle log data, where each log corresponds to a distinct operation. Where the mission is considered a complete workday, reflecting the operational cycle from the start to the end of the driver's day. This comprehensive definition allows for the identification of critical BEV-specific challenges, such as the need for frequent recharging due to the limited range of BEVs compared to ICE vehicles [7].

This mission-based approach facilitates the simulation of realistic operating conditions, including payload variability and stop duration, both of which are essential for accurately evaluating the performance of BEVs. For instance, payloads can vary substantially during a mission based on delivery requirements. Capturing these fluctuations within the model is crucial to ensuring precise predictions of energy consumption [5].

2.2 Driver

The development of an accurate driver model is essential for effective forward simulation, as it ensures a realistic representation of driving behavior by responding to real-time environmental inputs. A robust driver model is capable of generating realistic driving cycles, enabling meaningful simulation outcomes.

A driver model can be divided in three hierarchical levels. A *Strategic* driver, which determines the optimal route to get to the destination; a *Tactical* driver, scanning the environment to determine suitable acceleration and deceleration levels, and ensuring safe and efficient driving behavior by considering various factors (e.g. slowing down before a turn, a stop sign etc.); finally, an *Operational* driver level handles low-level control, using inputs like accelerator and brake pedals to achieve the desired speed or set-points defined by the tactical level [5].

The driver model developed in this project includes both tactical and operational levels, while the strategic level is not required as the route (to Viared and back) is known.

2.3 Vehicle

Vehicle modeling, particularly for electric vehicles, has been extensively studied to optimize energy efficiency and performance. Drivetrain modeling incorporates gear ratios and efficiency, with constant efficiency often assumed in energy-focused simulations. Battery models integrate power requests to estimate the state of charge (SOC), accounting for usable capacity constraints and regenerative braking efficiency. Aerodynamic drag follows principles outlined by Hucho [8], while rolling resistance models, as developed by Hyttinen et al [9], factor in tire temperature. Total energy consumption also includes auxiliary loads, while force dynamics—encompassing propulsion, drag, and grade effects—are modeled using frameworks from Rajamani [10]. These methods collectively ensure accurate representation of longitudinal vehicle dynamics and energy use, with potential for further refinement through adaptive efficiencies.

3 Simulation Model

There are several different ways of simulating energy consumption of a vehicle, however two are the most commonly used ones: Backward and Forward simulations [?].

In a *Backward* simulation the target speed is set by a driving cycle from log data of real vehicles. Newton's second law is applied to compute the required propulsion or braking force and the vehicle parameters are adjusted to replicate the speed profile accurately. This method is computationally efficient, however it requires log data from the same vehicle, as different vehicles are driven differently.

In a *Forward* simulation model the target speed is determined by a driver model, which interprets the real time information coming from the environment model and provides the pedals positions to the vehicle model. The vehicle model, finally, solves Newton's second law equation and integrates the vehicle kinematics, which are fed back to the environment and driver models. This method is more computationally expensive, but it allows a more fair comparison between electric and diesel tractors, as the driving cycles of the BEV will significantly differ from ICE trucks. For this reason, using Matlab ans Simulink, a Forward Simulation model has been developed for the study.

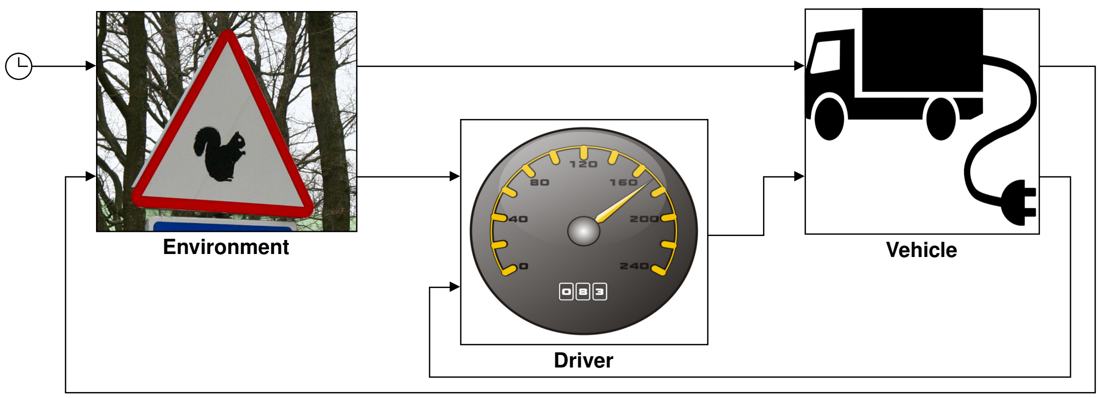

Figure 2: Forward simulation scheme.

In conclusion, since energy consumption is subject of this analysis, a point-mass vehicle model including only the longitudinal dynamics is considered.

3.1 Environment Model

The environment model is systematically divided into four distinct subgroups: *road*, *weather*, *traffic*, and *mission*. These subgroups are designed to be both flexible and intuitive, facilitating the design of detailed missions and simulations. This categorization aims to provide realistic environmental parameters critical for accurately describing transport missions.

Each subgroup encompasses specific parameters that collectively define the Operating Cycle (OC), as detailed in Table 1. For broader applicability, the OC may be referred to as the *Environment*, as it encapsulates all relevant factors influencing the simulation. This nomenclature emphasizes its comprehensive scope in representing environmental influences.

This structured framework ensures an accurate representation of all environmental elements, offering a reliable basis for realistic transport mission modeling. Additionally, the model incorporates predictive capabilities by providing the driver with detailed road information extending up to 300 meters ahead of the vehicle, thereby enhancing situational awareness and enabling proactive decision-making.

Table 1: The parameters that define the OC-format

Parameter	**Subgroup**	**Unit**
Speed limit sign	Road	m/s
Stop sign	Road	s
Curvature	Road	1/(100 m)
Road grade	Road	deg
Atmospheric temperature	Weather	°C
Atmospheric pressure	Weather	Pa
Air density	Weather	kg/m^3
Wind speed	Weather	m/s
Wind direction	Weather	deg
Free flow speed	Traffic	m/s
Traffic density	Traffic	1/m
Congested traffic density	Traffic	1/m
Mission stop	Mission	s
Cargo weight	Mission	kg
Travel direction	Mission	-

3.1.1 Road

The road category parameters include elements of road infrastructure that provide essential information to the driver, such as speed limits, stop signs, and road grade. These parameters serve to guide driver behavior and influence decisions based on the prevailing road conditions. For example, speed limit signs indicate the maximum allowable speed (110 km/h), while stop signs and other regulatory signs ensure compliance with traffic rules. Additionally, the road grade, which reflects the slope of the road, can affect vehicle performance and fuel consumption. These parameters are critical for simulating realistic driving scenarios and assessing vehicle dynamics.

Key Parameters
Speed signs regulate vehicle speed to ensure compliance with traffic safety standards. In their absence, default limits based on local regulations are applied: 50 km/h in urban areas, 70 km/h on non-urban roads, and 110 km/h on highways. These predefined limits ensure safety and efficiency, enabling vehicle models to simulate realistic speed adjustments when sign data is unavailable.

Stop signs regulate traffic flow at intersections, requiring vehicles to stop for a specified duration. They are particularly crucial in urban and residential areas to reduce vehicle-pedestrian conflicts. In simulations, stop sign data ensures realistic driver behavior and compliance with traffic control measures.

Road curvature influences vehicle dynamics, affecting speed choice and stability, particularly in sharp turns. It also impacts energy consumption due to lateral forces like side slip. While often negligible in basic simulations, accounting for curvature is essential in advanced models involving high-speed turns or complex road geometries.

Topography, or road grade, refers to the vertical slope of the road, expressed in degrees. Uphill grades increase engine load and energy consumption, while downhill grades reduce load but may require more braking. Accurately modeling road grade is crucial for predicting vehicle performance, particularly for electric vehicles, as it directly impacts battery usage and regenerative braking efficiency.

By integrating these parameters and taking position feedback from the vehicle model, the subsystem provides the driver with detailed environmental data for up to 300 meters ahead of the vehicle, ensuring informed and adaptive driving decisions.

The methodology for the road subsystem utilizes the Deterministic Operating Cycle (Doc) approach, dynamically extracting road parameters based on the vehicle's real-time position, from vehicle model's feedback, along the route. The function identifies the corresponding road segment from position based data of the trip. For each segment, attributes such as free-flow speed, road grade, stop signs, curvature, and speed limits are retrieved.

A look-ahead capability is incorporated, accounting for a predefined distance (300 meters) to anticipate upcoming changes in speed limits, road curvature, or other conditions. The function actively detects and incorporates variations in these parameters along the route, allowing the driver to act on the road conditions ahead.

3.1.2 Weather

In this model, we do not rely on external meteorological data providers, such as the Swedish Meteorological and Hydrological Institute (SMHI), or similar services for several reasons. One primary concern is the high spatial and temporal resolution required for real-time vehicle simulations. These simulations may involve fast-changing environmental conditions, and publicly available data from such services typically provide aggregated values over relatively large areas and time intervals. This level of granularity is often insufficient to accurately capture localized weather variations that can significantly affect vehicle performance. Furthermore, integrating external weather data would introduce additional complexities, including challenges related to data synchronization, coverage limitations, and potential concerns about data accuracy, particularly in remote or less-monitored regions. By opting for a simplified approach based on vehicle position and deterministic weather patterns, we ensure greater control over the model's accuracy, flexibility, and computational efficiency. This approach allows the model to operate effectively in real-time without reliance on external systems or data feeds.

The weather category within this model encompasses the time-varying physical characteristics of the environment, excluding the road itself. It includes parameters such as ambient temperature, ambient pressure, air density, wind speed, and wind direction, all of which influence vehicle performance but are not directly tied to the road or other vehicles. These parameters are treated as functions of vehicle position alone within the context of the deterministic Operating Cycle (OC) format.

To accurately model ambient temperature, the proposed approach distinguishes between two components: a deterministic component that captures diurnal and seasonal trends, and a stochastic component that accounts for random fluctuations throughout the day. This distinction enables a comprehensive representation of ambient temperature behavior. The model is expressed as:

$$T_{\mathrm{air},k} = \overline{T}_k + \tilde{T}_k, \tag{1}$$

where k represents a specific time of day.

The term $\overline{T}_k$ represents the deterministic trends, encompassing daily and seasonal variations, while $\tilde{T}_k$ denotes the stochastic component, capturing random fluctuations in temperature.

The deterministic components $\overline{T}_k$ are modeled as:

$$\overline{T}_k = \mu_T + T_d \sin\left(-\overline{\omega}_d k + \phi_{T_d}\right) + T_y \sin\left(-\overline{\omega}_y k + \phi_{T_y}\right), \tag{2}$$

where μ_T represents the average temperature. The daily and annual frequencies of the periodic signal are defined as $\overline{\omega}_d = 2\pi/(24 \cdot K)$ and $\overline{\omega}_y = 2\pi/(24 \cdot 365 \cdot K)$, respectively. Additionally, T_d and T_y represent the amplitudes of the daily and yearly temperature variations, respectively. The terms ϕ_{T_d} and ϕ_{T_y} denote the phase shifts that align the sinusoidal components with observed temperature patterns.

The stochastic components $\tilde{T}_k$ are modeled as:

$$\tilde{T}_k = \phi_{T|s_i} \tilde{T}_{k-1} + e_{T,k}, \quad e_{T,k} \mid S = s_i \sim \mathcal{N}(0, \sigma^2_{e_T|s_i}), \tag{3}$$

where $\phi_{T|s_i}$ and $\sigma_{e_T|s_i}$ are parameters that explicitly depend on the season S_i, with $i = 1, 2, 3, 4$.

The process variances are conveniently expressed as:

$$\sigma^2_{T|s_i} = \frac{\sigma^2_{e_T|s_i}}{1 - \phi^2_{T|s_i}}, \tag{4}$$

which reformulates the variance of the process $\sigma^2_{T|s_i}$ in terms of the variance of the error term $\sigma^2_{e_T|s_i}$ and the squared autoregressive coefficient $\phi^2_{T|s_i}$.

This formulation allows the model to effectively capture predictable seasonal patterns and inherent randomness in ambient temperature fluctuations, providing a robust framework for analyzing environmental influences on vehicle performance.

In contrast, *wind speed* and *direction* are modeled as deterministic operating conditions (DOC) based on the vehicle's position, similar to the approach used for the road subsystem.

Atmospheric pressure is also modeled as a DOC based on the vehicle's position, following a methodology analogous to that used for the road subsystem.

Air density, a critical factor influencing the aerodynamic drag experienced by the vehicle, is determined using the ideal gas law. The relationship is expressed as:

$$\rho = \frac{P}{R \cdot T} \tag{5}$$

where ρ represents the air density, P denotes the atmospheric pressure, T is the absolute ambient temperature in Kelvin, and R is the specific gas constant for dry air ($R = 287.05\,\mathrm{J/(kg{\cdot}K)}$).

This formulation allows for an accurate representation of air density by incorporating variations in pressure and temperature, both of which are influenced by the vehicle's position and surrounding environmental conditions.

3.1.3 Traffic

Traffic Flow Model is a foundational concept in traffic engineering that describes the relationship between *traffic density* (ρ) and *vehicle speed* (v). The Greenshields model [11] assumes a linear relationship between the two, providing a straightforward method for understanding how traffic behaves as congestion increases. This can be expressed mathematically as:

$$v_t = v_{\mathrm{ff}} \left(1 - \frac{\rho_t(x,t)}{\rho_c}\right), \tag{6}$$

where v_t is the speed of vehicles at a given density ρ and $\rho_t(x,t)$ is the istantaneous traffic density (vehicles per kilometer).

Free flow conditions represent a road segment's state when traffic is unobstructed, allowing vehicles to travel at optimal speeds without interference. The *free-flow speed* (v_{ff}) is the speed at which vehicles travel when there is no other vehicle on the road (i.e., when $\rho = 0$). This represents the maximum possible speed that vehicles can travel under ideal conditions.

Congested traffic density (ρ_c) represents the maximum traffic density at which the road becomes fully saturated with vehicles, causing the flow of traffic to halt. At this point, vehicle speed v reaches zero, indicating complete congestion.

3.1.4 Mission & Standstill

The mission subsystem provides information such as the cargo weight, the mission stop time and the travel direction. Such parameters can change only during standstill conditions and affect the whole simulation. In particular, the vehicle total weight is set to 55 tons for the delivery trip and to 25 tons for the journey back to the customer.

When the vehicle reaches the end of each trip it is important to manage the vehicle's **standstill**, avoiding the integration of zero speed and acceleration. This is because Simulink reduces the simulation step size when the integrand is zero, leading to extremely long simulation times. To address this issue, a further subsystem has been introduced in the Simulink model.

The **Standstill** block evaluates the vehicle's position and speed to determine if the truck is stationary and it identifies the vehicle's location (i.e. either in the harbor or at the customer). When a stop is identified the block outputs a *true* boolean signal.

This boolean allows to switch the environment's operating cycle from *'ToCustomer'* to *'ToHarbor'* and viceversa; it allows the tactical level of the driver to provide a zero speed request and it acts on the integrators of the vehicle model.

Specifically, detecting a mission stop halts the vehicle kinematics integrators and resets them to zero, ensuring compatibility with the environment's functional requirements. Meanwhile, the battery subsystem receives an integer signal indicating the 'battery state', to switch from the '*drive*' mode to either '*recharge*' or '*off*' modes. At the customer, the off mode is set as charging is assumed to be possible only at the harbor, while the recharge mode is set at the harbor when the battery SOC is lower than 40%.

The standstill condition is maintained for a period of time equal to the mission stop time provided by the mission subsystem. After this period elapses the simulation continues its normal operation.

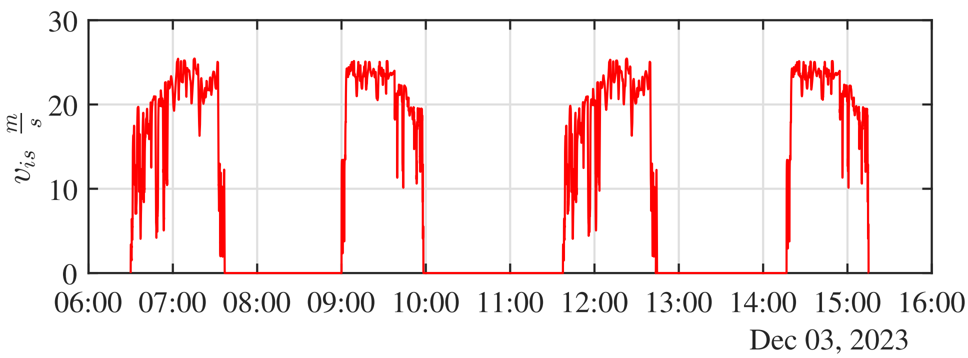

Figure 3: Speed profile for a day mission.

Fig. (3) shows the resulting speed profile of a simulation. The three mission stops (2 at customer and 1 at Gothenburg harbor) can be identified.

3.2 Driver Model

The driver model tries to mimic the behavior of a human driver, enabling realistic simulations of driving scenarios. It processes inputs like the road curvature, road traffic, stop signs and speed limits to define a speed profile and it determines the accelerator and brake pedals positions to achieve the mission with the maximum possible speed.

The top level of the driver model is split into two parts, a **Tactical Driver** and an **Operational Driver**, which will be discussed in the next paragraphs.

3.2.1 Tactical Driver

The tactical driver determines the required speed in real-time by considering environmental parameters categorized into four subsystems: speed limits, stop signs and traffic lights, road curvature, and traffic conditions. The speed limit introduces a straightforward threshold, v_{SL}, while stop signs and traffic lights impose a mandatory standstill condition ($v_s = 0$) for a specified duration. Traffic conditions are modeled using equation (7):

$$v_t = v_{\text{ff}} \left(1 - \frac{\rho_t(x,t)}{\rho_c}\right) \tag{7}$$

Finally, road curvature imposes a constraint based on the maximum lateral acceleration, a_{y0}, which defines the maximum allowable speed as:

$$v_\kappa = \sqrt{\frac{a_{y0}}{\kappa}} \tag{8}$$

These active parameters are visible to the driver up to a look ahead distance of 300m, allowing for proactive speed planning, such as slowing down before a curve or a stop sign.

Introducing a maximum deceleration a_{x0}, perceived as comfortable by the driver, it is possible to model the prediction speed v'_p given the parameters ahead with the following equation:

$$v'_p = \sqrt{v^2_{p,i+1} + 2a_{x0}(X_{i+1} - x)} \qquad [5], \tag{9}$$

where $v_{p,i+1}$ is the speed constraint associated to parameter p at position X_{i+1}.

Assuming that the driver's objective is to maximize the speed while respecting these legal and physical constraints, the required vehicle speed v_{req}, sent to the operational level, is determined as the minimum amongst the previously described constraints.

$$v_{req} = min(v_{SL}, v'_{SL}, v_s, v'_s, v_\kappa, v'_\kappa, v_t, v'_t) \tag{10}$$

Additionally, the model includes a drive state input that identifies whether the vehicle is stationary, such as during loading, unloading, or recharging activities, or in motion. This feature serves as a system enabler to provide a zero-velocity output when the vehicle is in standstill condition.

3.2.2 Operational Driver

The operational part of the driver model is a simpler system that functions similarly to a cruise controller. Once the tactical driver determines the required speed v_{req}, the accelerator and brake pedals must be regulated so that the vehicle follows this speed profile.

A P-controller computes the error between the required velocity and the current vehicle speed. Based on this error, the P controller adjusts the output to control the accelerator and brake pedals, effectively managing the vehicle's speed. The accelerator and brake pedal position (γ_a and γ_b respectively) outputs are set between 0 and 1. Low pass filters are used to avoid torque request impulses to the vehicle and emulate real driving behavior.

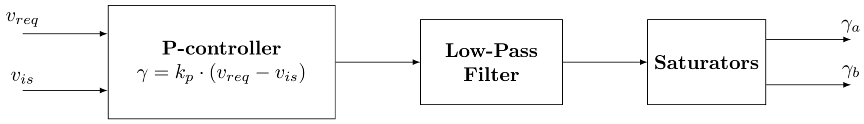

Figure 4: Operational Driver flowchart

Figure. 5 shows the resulting driving cycle and the actual vehicle speed. The largest differences can be identified where a severe uphill is present (e.g. a 7% uphill slope is reached at 06:50), as the vehicle weighing 55 tons cannot achieve the speed limit.

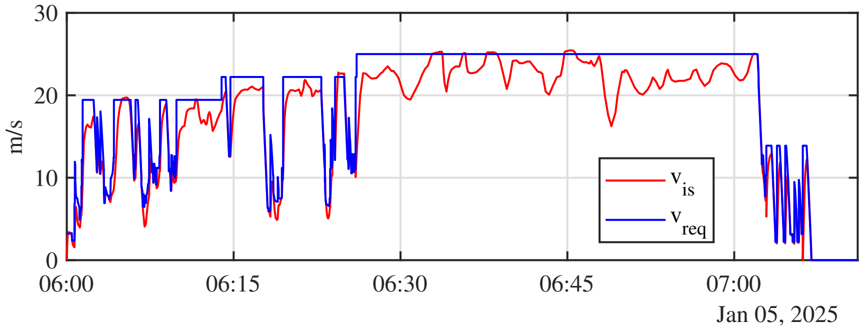

Figure 5: Driving cycle v_{req} and vehicle speed v_{is} for the trip to the customer.

3.3 Vehicle Model

The vehicle under analysis, an A-double combination displayed in Fig. (1), is modeled as a point mass, with one equivalent tyre that accounts for all tyre forces experienced by a truck. Additionally, as it is done for most energy consumption or battery sizing simulations, only the longitudinal dynamics of the vehicle are considered.

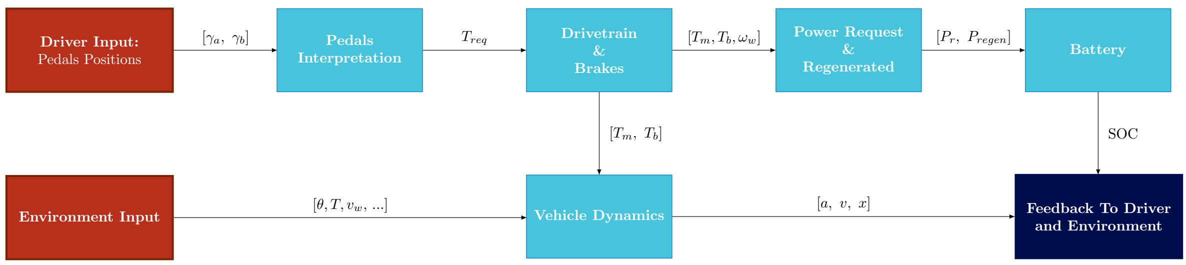

Figure 6: Vehicle model

3.3.1 Pedal Interpretation

Taking as input the accelerator and brake pedals positions, this block computes the motor torque T_m and the braking torque T_b requested by the driver. Both are computed by scaling the maximum motor and braking torque by the respective pedal's position.

$$\begin{cases} T_m = \gamma_a \; T_{m,max} \\ T_b = \gamma_b \; T_{b,max} \end{cases} \tag{11}$$

The motor torque is also constrained by the rated power P_r, ensuring $T_m \cdot \omega_m < P_r$.

3.3.2 Drivetrain

The drivetrain block computes the motor torque transmitted to the wheel. The modeled drivetrain is the Volvo I-Shift transmission, with gear shifts programmed at specific vehicle speeds.

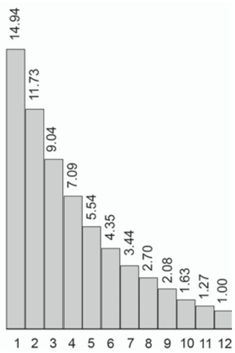

Figure 7: Gear ratios of Volvo I-Shift gearbox

3.3.3 Total Power Requested/Regenerated

This block determines the total power drawn from and regenerated back into the battery. It also accounts for auxiliary power consumption, which includes cabin heating, battery heating and cooling, radiator operation, and pump losses.

For the regeneration power computation it has been assumed that 30% of the total braking power is regenerated back into the battery, with a maximum of 200 kW (equal to the recharger power).

3.3.4 Battery

The battery under consideration has a total capacity E_{cap} of 540 kWh. However, to account for practical constraints, only 85% of the total capacity is assumed to be usable, resulting in an effective capacity of 459 kWh.

The battery model calculates the SOC by integrating the power request. The modeled battery includes three states (*drive*, *recharge* and *off*). During the *drive* state, the integrand is the power requested or regenerated, while in the *recharge* state, a constant recharge power of 200 kW is assumed. When the vehicle is in the *off* state, instead, the integration is halted.

3.3.5 Vehicle dynamics

This block models all the different forces acting on the vehicle, including propulsion, braking, rolling resistance, aerodynamic drag, and road grade effects. Newton's second law is than used to compute the vehicle's acceleration and, by integration, the speed and position are obtained.

The **aerodynamic drag** force is modeled using the primary drag force equation:

$$F_d = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V^2, \tag{12}$$

where ρ is the air density, C_d the aerodynamic drag coefficient, A_f is the vehicle's frontal area and, finally, V is the relative speed between truck and wind. In equation (12), a constant drag coefficient C_d has been considered and the effects of cross wind on the vehicle have been neglected.

The **rolling resistance** force F_{rr} is modeled based on a tyre temperature-dependent rolling resistance coefficient C_{rr} [9].

$$F_{rr} = m \cdot g \cdot C_{rr}(T_t) \cdot cos(\theta) \tag{13}$$

The tyre temperature T_t is calculated based on the vehicle velocity only. This has proven to be a limiting assumption since, contrary to the expectations, no differences in rolling resistance losses can be highlighted between winter and summer.

The final external action included in the dynamic equilibrium equation is the one due to the **road grade** θ:

$$F_\theta = m \cdot g \cdot sin(\theta) \tag{14}$$

In conclusion, the traction and braking forces, F_m and F_b respectively, are computed. Starting from the motor torque T_m from eq. (11), the traction force is given by:

$$F_m = \eta_m \eta_\tau \frac{T_m \cdot \tau(v)}{R_w}, \tag{15}$$

where η_m and η_τ are respectively the electric motor and the transmission efficiencies, both assumed as a constant, $\tau(v)$ are the gear ratios and R_w is the wheel radius.

Finally, the braking force is obtained from the braking torque T_b as:

$$F_b = \frac{T_b}{R_w} \tag{16}$$

The vehicle acceleration is finally computed as:

$$a = \frac{1}{m}(F_m - F_b - F_{rr} - F_\theta - F_d) \tag{17}$$

By integrating eq. 17 the vehicle speed v_{is} can be obtained and the vehicle position is obtained with a second integration.

4 Results

4.1 Case Study

The current mission model begins with the trip departing from Gothenburg Harbor at 6:00 AM. A loading time of approximately 30 minutes is required, with the loading process completed by 6:30 AM. At this point, the vehicle departs the harbor and travels toward Viared, covering a distance of 74 km.

Upon arrival at Viared, the vehicle performs a series of local operations, covering a distance of approximately 1.5 km. These operations are as follows:

1. **Uncoupling the second trailer and dolly** in the Dry Port area.
2. **Hauling the first trailer** to the final customer in the Viared area.
3. **Picking up an empty trailer** and returning it to the Dry Port.
4. **Uncoupling the dolly** and hauling the second trailer to the final customer in the Viared area.
5. **Picking up another empty trailer** and returning it to the Dry Port.
6. **Re-coupling the trailers** with empty containers and the dolly into an A-double configuration.

This sequence of operations typically takes around 1 hour to complete. After finishing these tasks, the vehicle departs Viared and heads back to Gothenburg Harbor, carrying empty containers (total vehicle weight of 25 tonnes). Upon arrival at the harbor, the vehicle undergoes another shunting operation. During this process, the vehicle is recharged, and the containers are loaded. Data provided by Volvo on container loading times at the harbor have been incorporated into the model, as illustrated in Fig. (8).

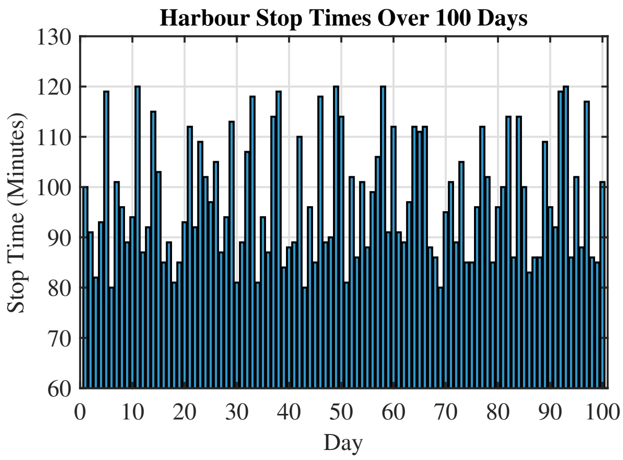

Figure 8: Harbor recharge time over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Once the vehicle is loaded, the next trip commences, following the same operational sequence as the initial trip.

The cargo weight for this mission was obtained from Autofreight data. The gross weight of the A-double combination is approximately 55 tonnes. The weight breakdown is provided in the table below:

The results obtained through the forward simulation modeling approach were analyzed on a daily basis. The analysis relies on several assumptions.

Parameter	Value
Kerb weight of the combination	25 tonnes
Cargo weight	30 tonnes

Table 2: Weight distribution of the A-double combination

The study considers a total of 100 operational days, distributed across the four seasons. This sample size was chosen to ensure a manageable, yet statistically meaningful, representation of typical operations, while also maintaining computational efficiency. A larger sample size would significantly increase computational resources and time, while a smaller sample might fail to capture the variability and seasonal effects. Therefore, 100 operational days were selected as an appropriate balance.

The simulation assumes only one charging station located at the Gothenburg Harbor and that a single BEV tractor is used for both highway driving and local distribution. The gross weight of the A-double combination is 55 tonnes, and the operation is carried out with a single driver. For the energy cost comparison between the electric and diesel tractor, a constant 3 SEK/kWh has been assumed for electrical energy and 18 SEK/L for the diesel fuel.

4.2 Key Energy Metrics

The key energy metrics considered for the BEV include daily energy consumption, auxiliary energy consumption, recharged energy and regenerated energy.

Required energy: The following Fig. (9) shows the total energy request for the four trips between Gothenburg and Viared. It can be seen that for every day the total energy consumption is above the available battery capacity, showing a maximum of 691 kWh and a minimum of 525 kWh (respectively 1.5 and 1.15 times the available battery capacity). This proves the need for recharging during the daily operations.

It can also be noted that the simulation outcomes do not show significant changes in energy consumption for different seasons.

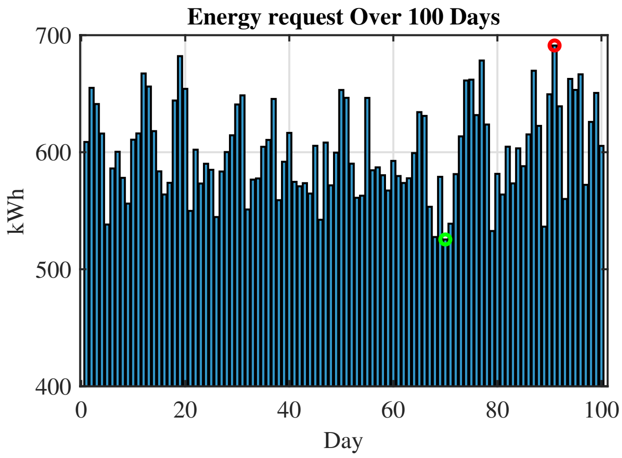

Figure 9: Required energy (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Auxiliary Energy Consumption: A notable variation is observed in auxiliary energy consumption, depicted in Fig. (10). As expected, the highest consumption of around 60 kWh occurs during winter, in contrast, summer records the lowest auxiliary energy consumption at around 10 kWh. Nonetheless, energy consumption due to auxiliaries cannot be distinctly identified within the overall energy consumption, as these seasonal variations are approximately 50 kWh, while daily fluctuations of Fig. (9) are significantly larger.

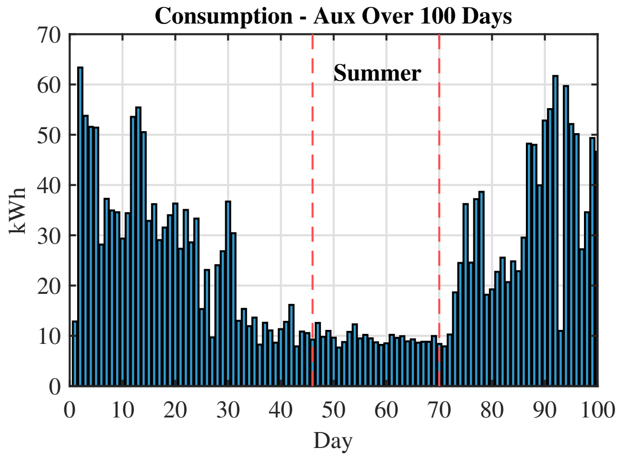

Figure 10: Auxiliary energy consumption over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Regenerated Energy: As shown in Fig. (11), the regenerated energy does not show significant variation across different seasons as road conditions are not included in the study. The average daily regenerated energy is of 45 kWh, consisting of around 10% of the available battery capacity.

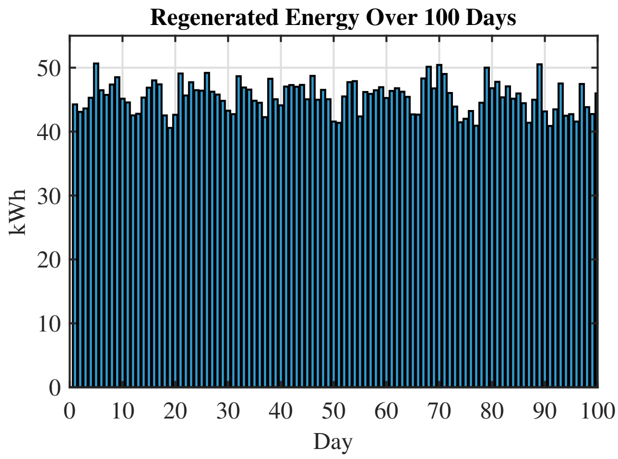

Figure 11: Regenerated energy over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Recharged Energy: The recharged energy, as illustrated in Fig. (12), do not exhibit periodic peaks. The observed daily fluctuations in recharged energy are primarily attributed to the aleatory durations of harbor stop times. The recharged energy ranges between 350 kWh and 265 kWh, which represent respectively 65% and 49% of the battery capacity.

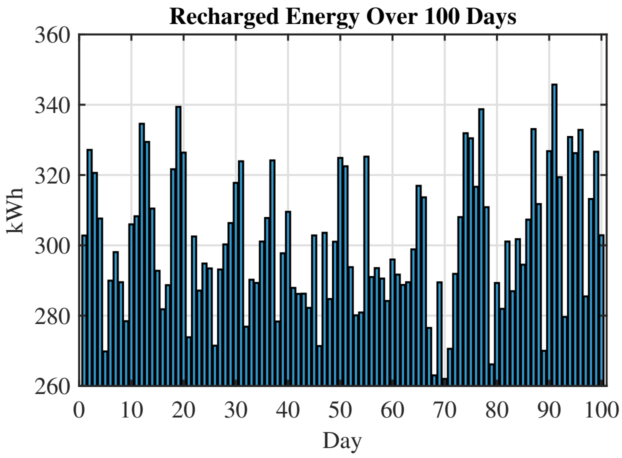

Figure 12: Recharged energy over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Summary: Fig. (13), showing the average daily energy consumption terms, summarizes the trends of the energy losses over the four seasons. It can be seen that the only significant difference between the seasons can be attributed to the auxiliary energy consumption, while the model cannot capture the seasonal variation of the rolling resistance.

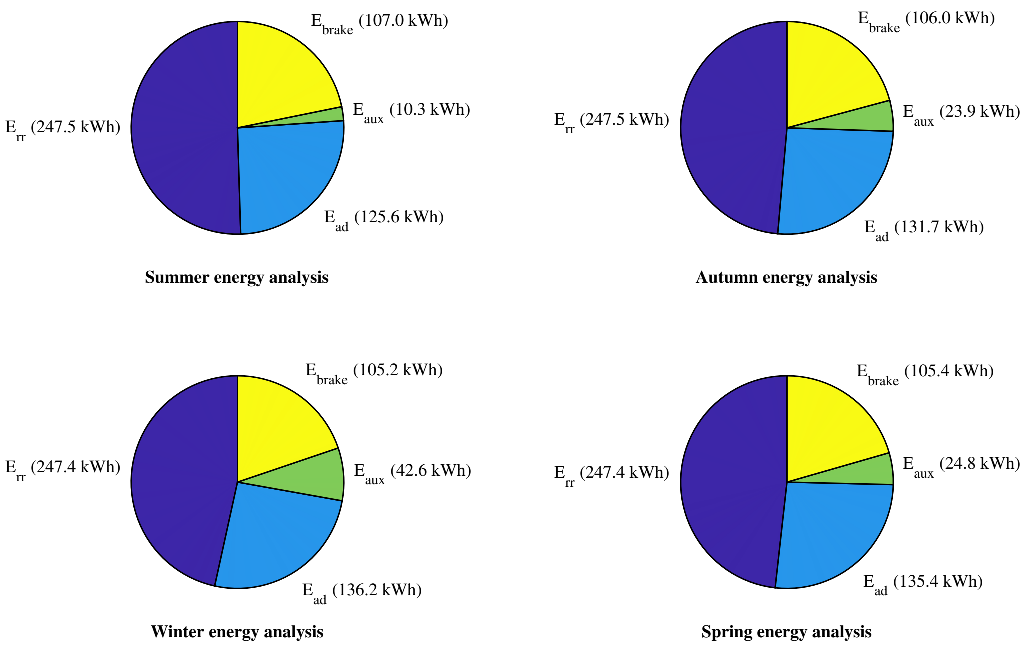

Figure 13: Average energy consumption shares across seasons over 100 days.

Nonetheless, the prevalence of rolling resistance over the other factors is expected and it reflects reality.

4.3 Energy Consumption per Kilometer: BEV vs. ICE Comparison

Simulations performed show that BEV's energy consumption varies depending on the route type. For highway routes (referred to as "Main"), the average energy consumption per kilometer is 2.35 kWh, with occasional peaks reaching 2.5 kWh/km. For local distribution routes, the energy consumption is higher, averaging 2.93 kWh/km, with peaks reaching 3.2 kWh/km.

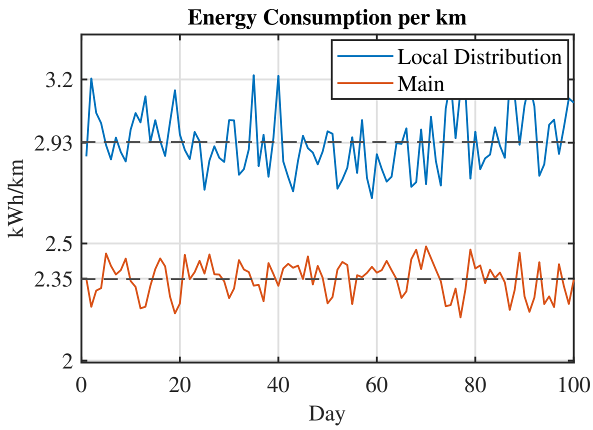

Figure 14: Energy consumption per kilometer over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

The higher energy consumption for local distribution routes is primarily due to operational factors such as frequent and sharper turns, which lead to frequent braking maneuvers.

In contrast, the energy consumption per kilometer for an ICE vehicle configured in an A-double combination, with a gross weight of 55 tonnes, has been analyzed using data from the Autofreight project [1]. These vehicles consume an average of 45 liters of diesel per 100 kilometers when loaded. Given that diesel fuel has an energy content of approximately 10 kWh/L, the energy consumption for a loaded ICE vehicle is calculated as:

$$\text{Energy Consumption:} \quad \frac{45L}{100km} \times \frac{10kWh}{L} = 4.50\,\text{kWh/km}.$$

For ICE vehicles operating with empty containers, fuel consumption is reduced to 35 liters per 100 kilometers, or 0.35 liters per kilometer, resulting in an energy consumption of:

$$\text{Energy Consumption:} \quad \frac{35L}{100km} \times \frac{10kWh}{L} = 3.50\,\text{kWh/km}.$$

This difference in energy consumption with respect to electric vehicles can be attributed to the lower efficiency of diesel engines compared to electric motors, especially under varying load conditions.

The comparison reveals that BEVs exhibit a more efficient energy usage. This indicates a clear advantage for BEVs, which consistently consume 25% to 45% less energy per kilometer than ICE vehicles, depending on the route type. Therefore, it can be conclusively stated that BEVs outperform ICE vehicles in energy efficiency on a per-kilometer basis.

4.4 Energy Cost

The breakdown of energy costs between the **Main Driving Route** (Gothenburg to Viared) and **Local Distribution** is illustrated in Fig. (15) below.

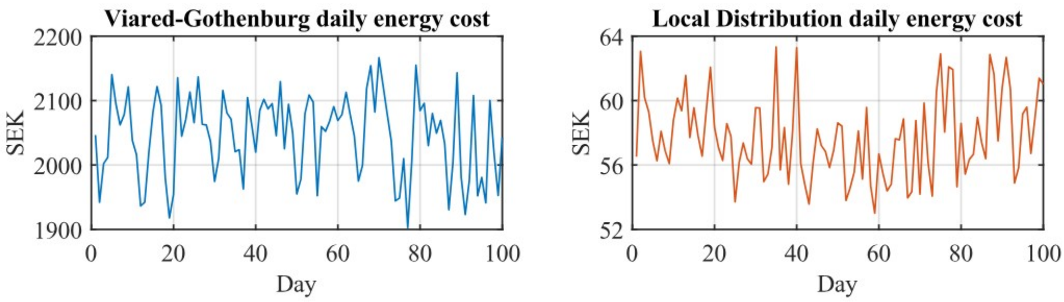

Figure 15: Energy cost over 100 days (Day 95–100 and 1–20: Winter; Day 21–45: Spring; Day 46–70: Summer; Day 71–94: Autumn).

Fig. (15) provides a comparison of the energy costs for the two route types. On the left, the energy costs for the **Main Driving Route** (Gothenburg Harbor to Viared and back) are displayed, while the costs for **Local Distribution** are shown on the right. The daily energy costs for the main route ranges from **1,900 SEK** to **2,150 SEK**, depending on the operational conditions. In contrast, local distribution incurs daily energy costs between **53 SEK** and **63 SEK**. Although the cost per kilometer for local distribution is higher, its energy cost accounts for just 3% of the overall daily energy cost.

The total energy cost incurred by the BEV over a period of 100 days is computed with a constant energy cost of 3 SEK/kWh and it sums up to approximately **180,000 SEK**.

In comparison, the energy cost for an ICE vehicle is calculated based on a fixed diesel price of 18 SEK/L. Assuming 75 kilometers of daily operation under both loaded and unloaded conditions over 100 working days, the total diesel cost c_d is computed as follows:

$$c_d = [(0.45\frac{L}{km} \cdot 75km \cdot 2 \cdot 100) + 0.35\frac{L}{km} \cdot 75km \cdot 2 \cdot 100] \cdot 18\frac{SEK}{L} = \mathbf{216'000\ SEK} \quad (18)$$

This formula accounts for the diesel consumption rates for loaded (0.45 L/km) and unloaded (0.35 L/km) conditions, with the factor of 2 reflecting a round trip.

When comparing the total energy costs of the ICE vehicle with the BEV under similar operating conditions, it becomes evident that the ICE vehicle incurs a **19.7% higher** energy cost.

4.5 Strategic Evaluation of BEV Deployment

This section consists of a brief discussion on questions 1-3, listed in the introduction, which could be relevant for prospective customers. From Fig. (16), showcasing a winter day operation, it can be seen that the battery state of charge is drained to 25% after each round trip, with a recharging stop long enough to completely recharge the battery.

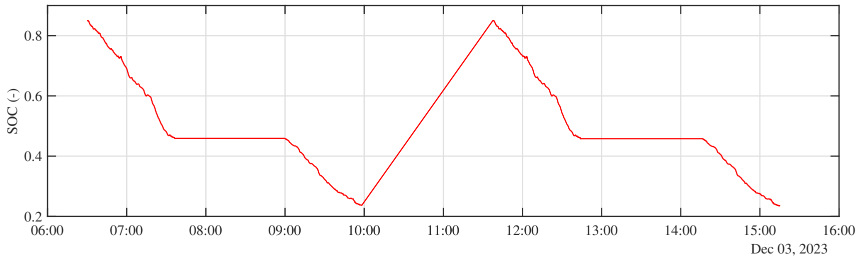

Figure 16: Battery State of Charge during a day

It should also be noted that the minimum battery SOC experienced by the vehicle in all simulations is above 15%. This indicates that, with all the limitations and assumptions included in the model, the BEV can complete the freight transport mission between Gothenborg and Viared and it is sufficient to use only a recharging station at the harbor.

In addition, the 100 simulations always end at around 3 p.m., thus resulting in 9 total hours, which include the driver's breaks. This means that a third delivery to the customer is not possible without either a second driver or a dry port in Viared.

5 Conclusion

In this project, a fully functioning Forward simulation model, including an environment, a driver, and a vehicle, has been implemented in Simulink to study the freight transport of customer goods from the Gothenburg harbor to Viared. A further subsystem has been introduced in the model to deal with the challenging standstill condition.

The model presents some limitations, nonetheless, thanks to a structured implementation, improvements can be easily introduced in future development of the project. In addition, the stop times, including recharging times, can be modified to better reflect real daily operations.

The seasonal analysis shows the trend of auxiliary energy consumption over the year, however, the results do not reflect the expected increase of rolling resistance during winter due to limitations in the rolling resistance model.

The results obtained by the 100 days of simulation, with all the assumptions cited in the previous chapters, show that the electric tractor can achieve the mission by recharging the battery just once a day at the harbor.

From simulation outputs it is also possible to see that, with one only vehicle and one driver delivering the containers directly to the final customer, it is not possible to achieve the third daily delivery. The addition of a second driver and a dry port in Viared may allow for the third delivery, however this has not been verified in the project.

In conclusion, the project highlights that the energy cost for running a battery electric truck is lower than the diesel cost for the state of the art diesel trucks. Nonetheless, a complete and comprehensive cost analysis of the operation is needed to determine the economic feasibility of adopting BEV trucks.

5.1 Future Scope

Thanks to a well structured implementation of the Simulink model, improvements can be easily introduced and added to the simulation. These include the addition of environmental factors such as road roughness, precipitations and speed bumpers.

An enhanced version of the battery model and rolling resistance coefficient including the effects of temperature, could provide a more realistic assessment of energy consumption. This could also be achieved by introducing the effects of the road topography on driving behavior.

Concerning the case study, it would be possible, with few modifications on the model, to consider a second driver and a dry port at Viared to potentially carry out a third delivery. The possibility of recharging at Viared could also be introduced to analyze possible strategies to maximize the efficiency of the operation.

Finally, the development of an ICE vehicle would allow for a more detailed estimation of diesel cost, thus a more fair comparison between the two trucks.

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