THE USE OF HYBRID TRUCKS IN FOREST TRANSPORTS




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Abstract

This paper explores the application of hybrid log trucks in forest transportation, focusing on their ability to recuperate energy through regenerative braking. A novel energy consumption model is proposed to estimate the energy requirements of hybrid trucks with the help of insights gained from a physical test. The model estimates the overall diesel consumption along a route by an empirical-based approach, where speed and slope serve as independent variables. The electrical energy contribution is quantified for different slopes, distinguishing energy dynamics for downhill and uphill segments. To ensure the truck's electrical batteries never run out of energy, a dynamic rule-based driving strategy is implemented. The model calculates the overall energy savings in each drive cycle. This methodology is tested on two sample drive cycles selected from the province of Quebec. Results indicate that hybrid electric trucks are well suited for long-distance hilly routes compared to short- distance driving.

Keywords: Forest transportation, Hybrid trucks, Energy efficiency, Regenerative braking, Profile analysis.

1. Introduction

In recent years, heavy freight electrification has proven to be a promising technology for reducing fuel consumption for transporting wood and other forest products (Noreland,2024). Battery electric trucks (BET) help compensate for the low powertrain efficiency of diesel engines. However, the heavy battery weight, limited driving range, and loss in the transported payload are challenges for fleet owners. To overcome these limitations, parallel hybrid electric trucks are considered suitable alternatives. One of the advantages of using a hybrid electric log truck in log hauling is that the vehicle's potential energy can be partially recovered and stored by regenerative braking, especially when driving down mountains. Parallel hybrid electric architecture has the advantage of reduced battery size and a mechanism of direct mechanical power transfer from the engine to the wheels. A series hybrid, although engines operate at high efficiency, the multiple energy conversions from mechanical to electrical and reverse can lead to energy losses. The average overall efficiency of such architecture is 25%. In contrast, the parallel hybrid allows both engine and batteries to support the propulsion, thus improving overall efficiency. The average overall efficiency is between 45% and 50%, desirable for long-haul highway driving applications (Williamson,2013).

Due to a shortage of hybrid electric log trucks, Canada-based R&D organization FPInnovations conceived the idea of developing a prototype electric trailer for long-haul timber transports. It was equipped with data loggers to collect GPS data and was driven in tandem with a conventional diesel truck using the SAE J1321 test procedure (Rosenthal, 2008). In the test, data was collected from an instrumented vehicle alongside a standard one. The objective of the test was to evaluate the impact of using an electric trailer on fuel economy. During the procedure, when the truck ran on pure diesel mode on the test route, the truck consumed up to 72 Liters/100km. Using electric motors, the truck consumed 63 Liters/100km, saving up to 13% of diesel. Also, the electric battery had a 30% increase in state of charge (SOC) and energy recuperation from 0.25 kWh/km to 0.30 kWh/km. Data-driven models help to contextualize the findings of the physical test to different route profiles.
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Since analyzing hybrid trucks is a complex process, the applications of predictive cruise controls (PCC) have garnered a lot of interest. PCC allows trucks to adjust their speed when approaching a hill and avoid unnecessary downshifts. PCC uses road profile information and adjusts speed to maintain the vehicle momentum for the next hill. A big challenge in forest transportation often comprises numerous ups and downs, sharp turns and curvatures, and icy roads. It makes it harder for PCC systems to predict future road conditions. In Quebec, Samson et al. (2021) introduced the MapEUR (Map of Energy Use on Road), a practical tool integrating multiple mathematical models to evaluate truck energy consumption, with results displayed on a road map. Inputs to the model included road network properties and the characteristics of different heavy vehicles. The model estimates the vehicle speed profile, and the output is a geolocated dataset detailing energy consumption for each road segment. In Sweden, Noreland (2024) utilized a semiempirical model for driving speed simulation and energy use estimation for timber trucks. The study involved a two-phase analysis: first, applying a kinematic model to simulate the driving pattern, followed by a mechanistic model on the simulated speed profile to compute fuel use, driving time, and energy consumption for different drivers on the same route. The author attempted to separate technical and human factors by developing a robust model to handle extreme driving conditions in timber transport.

Looking at the challenges of dynamic speed changes, this paper introduces a generic data-driven model for estimating the overall energy consumption of hybrid electric trucks in forest transportation. The model is a 2nd-degree polynomial with road slope and speed as independent variables. It is solved using the least squares regression method. Using measured data from the prototype as a training dataset, our model first predicts total diesel consumption along a given route. Further, we estimate the proportion of electrical energy drawn from the batteries relative to different road slopes. It helps to quantify the dynamic effects of electrical propulsion and regenerative braking for downhill and uphill road segments. The total energy is the difference between diesel and electrical consumption. Based on total energy consumption, we use a rule-based heuristic mechanism to adjust the energy consumption from the batteries. It helps to determine the overall savings in fuel consumption and the final state of charge of the battery. We test this methodology for hybrid trucks with different battery capacities. The findings from this study have practical implications for fleet owners, truck manufacturers, and policymakers.

The remaining paper is organized; Section 2 introduces our methodology. Section 3 presents a case study to discuss the application of the proposed methodology. Section 4 provides the results from our methodology and test cases. Section 5 is a brief discussion of the limitations of the analysis. Section 6 describes the conclusion and provides direction for future studies.

2. Materials and Methods

2.1 Description of the measured data

Powertrain hybridization provides advantages like reduced engine size, the use of a standalone electrical motor when the diesel engine shuts down at low speeds, and improved control systems in vehicle architecture. The electric motors assist the engine during uphill driving and energy recovery from downhill mountain driving through regenerative braking. The utilization of electrical motors can be quantified by scalar terms known as the electric hybridization ratio (EHR). A parallel hybrid electric architecture has a maximum EHR value of 30% to 45%. It is the ratio of the electric power to the total power consumed by the vehicle. In Table 1, the percentage distribution of electrical energy concerning the slope. In Figure 1, the scatter plot of electrical motor measurements observed throughout the drive cycle shows the relationship for different slopes. As the slope gradient increases, the use of the electric motor increases. This is also explained by the average values as seen in the EHR percentage.

Table 1- The Electrical hybridization ratio corresponding to a given slope range.

Road Slope (%)	Electrical Hybridization Ratio (%)		
	Mean	Maximum	Minimum

(0, 1)	6.46	42.49	0.55
(1, 2)	9.42	37.87	0.54
(2, 3)	22.69	37.82	0.82
(3, 4)	28.88	38.11	10.86
(4,5)	31.27	33.34	28.19
(5,6)	31.97	32.31	31.64

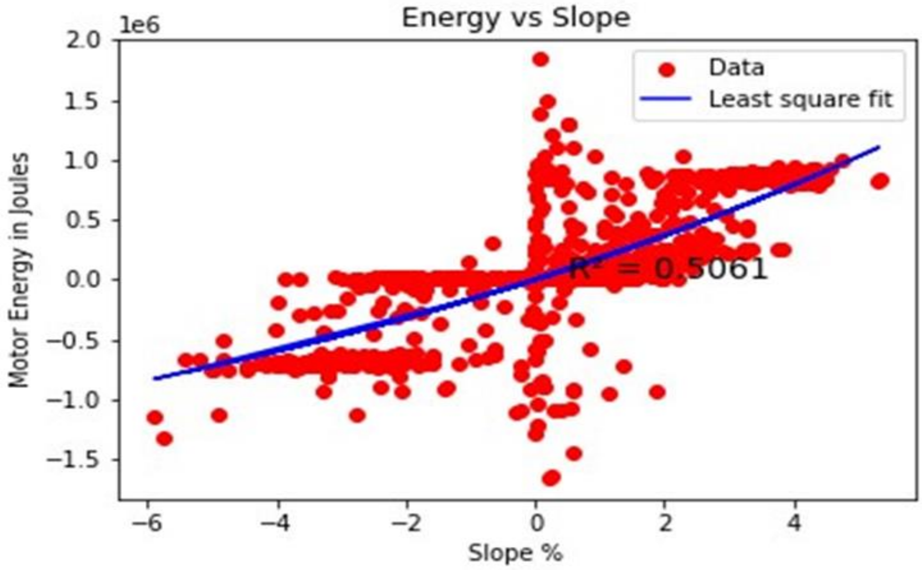


Figure 1- The relationship between the electrical motor energy and the road slope on the test route for every 100-meter measurement.

2.2 Methodology

The energy consumption of a hybrid electric truck for a given drive cycle can be obtained either empirically or physically. These models imperatively rely on high-quality road slope measurements to have accurate estimations. In this paper, the overall energy consumption is empirically estimated using a 2nd-degree polynomial. It is solved using the least square regression model. An advantage of such an approach is one need not know the physical interplay between engine subsystems and the impact of resistive forces. As the data was obtained at a 10 Hz frequency, we observed numerous inconsistencies in the slope information. The distance between each measurement was small (< 0.5 meters). Hence, we chose a 100-meter distance window to aggregate the dataset. For every 100-meter measurement, we obtained the average value of the slope, speed, SOC, and overall fuel and electric energy consumption. The polynomial regression problem is shown in Equation 1.

$$Min \;\; f(\beta) = \sum_{i=}^{N} (Y_{diesel} - (\beta_0 + \beta_1 S + \beta_2 S^2 + \beta_3 V + \beta_4 V^2 + (Mechanical \;\; Auxiliaries)))^2 \qquad (1)$$

Where $\beta_{0...4}$ = Regression coefficients. Y_{actual}= Measured fuel consumption in Liters/hour, the auxiliaries are a constant power off-take of 8 kW. We chose a polynomial of order 2 to balance the complexity of the model without the risk of overfitting. The polynomial can capture non-linear effects well. It was helpful in scenarios when the relationship between variables is not linear. As speed and slope directly impact fuel consumption, it allows for clear insights into the relationship between independent and dependent variables. The model is faster to train, test, and deploy. The model assumes that the speed of the truck is constant. The measured data obtained was from a highway drive cycle. Thus, it was hard to generalize numerous types of driving scenarios. The model does not consider the effects of road crossings, frequent braking, or road obstacles along the path. The model tends to underestimate energy consumption. The electrical energy consumption for a profile is found as a proportion of energy consumed for different slopes. There is a distinct lack of empirical data on the electrical energy consumption of heavy hybrid electric or electrical trucks. This can be found in physical fuel consumption procedures. Table 2 shows the different values of the slope, which is the proportion of electrical energy consumption provided by the electrical motor for propulsion and regenerative braking. Measured data was collected from a prototype hybrid electric truck installed with a GPS and CAN BUS system. The difference between the overall diesel consumption and energy from the electric motor estimates the fuel savings when using a hybrid electric truck.

Table 2- The average, maximum, and minimum speed, diesel, and electrical energy consumption of the hybrid electric truck for different values of road slope.

Slope in %	Truck Speed in km/h			Fuel consumption in Liters			Electrical energy consumption from the motors in kWh		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
-6 to -5	55.772	57.208	54.336	0.000	0.000	0.000	-0.315	-0.316	-0.313
-5 to -4	95.521	103.447	58.336	0.000	0.000	0.000	-0.205	-0.311	-0.183
-4 to -3	97.893	104.837	49.214	0.000	0.008	0.000	-0.188	-0.364	-0.009
-3 to -2	99.969	103.664	84.536	0.007	0.089	0.000	-0.127	-0.254	0.076
-2 to -1	98.786	103.533	80.905	0.018	0.103	0.000	-0.026	-0.249	0.224
-1 to 0	91.827	102.241	3.218	0.048	0.159	0.000	0.000	-0.459	0.307
0 to 1	91.212	100.616	17.819	0.076	0.176	0.000	0.023	0.510	-0.456
1 to 2	90.044	100.043	35.176	0.098	0.159	0.000	0.059	0.287	-0.197
2 to 3	88.070	97.921	62.717	0.102	0.145	0.077	0.113	0.247	0.003
3 to 4	78.162	94.144	41.594	0.117	0.145	0.088	0.192	0.274	0.013
4 to 5	72.979	83.422	63.626	0.121	0.144	0.096	0.241	0.260	0.220
5 to 6	67.565	77.503	58.025	0.117	0.119	0.116	0.232	0.232	0.232

2.2.1 Road Profile Analysis

Using the values from Table 2, the average energy savings of a drive cycle with a hybrid truck can be calculated. The main challenge lies in dynamically adjusting motor energy consumption along the route. To prevent the batteries from depleting, a rule-based heuristic strategy is implemented, ensuring the truck can operate on various types of roads. Figure 2 below illustrates a schematic representation of this rule-based heuristic method.

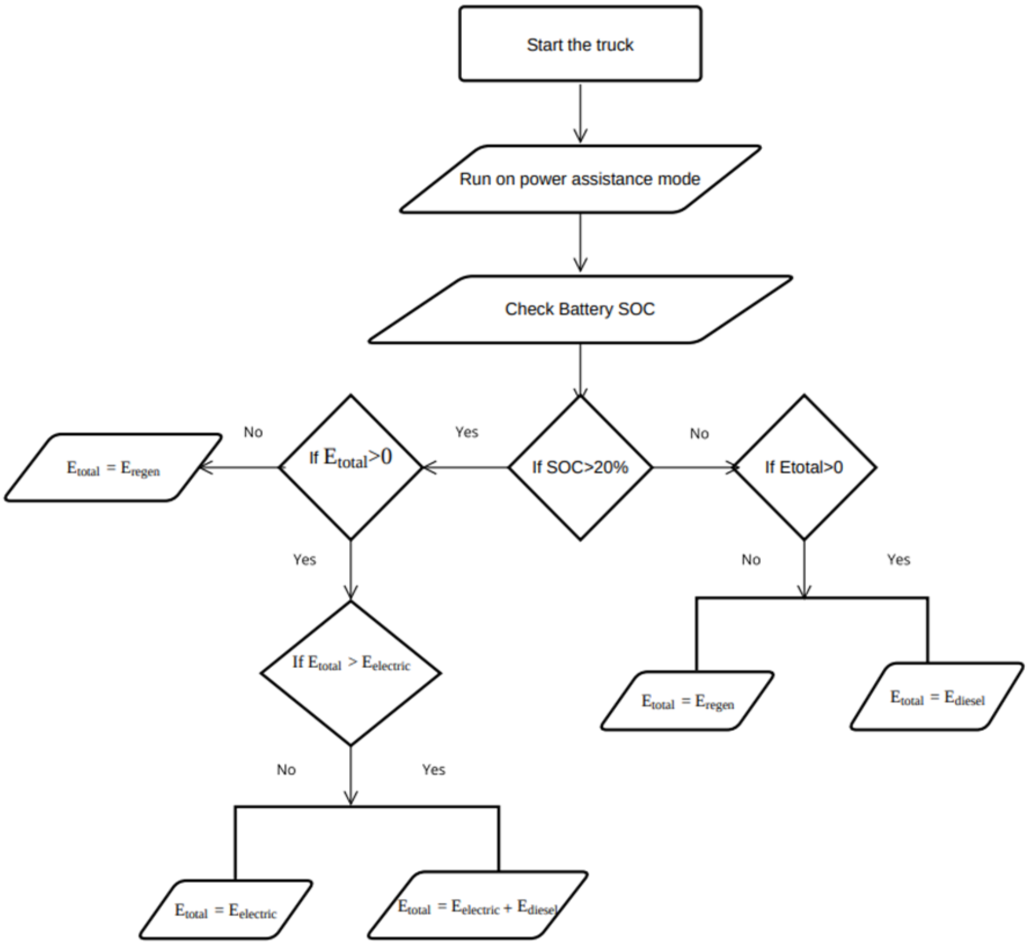


Figure 2- Rule-based driving strategy. Adapted from (Fiori et al., 2018).

From the above figure, the following notations are:

E_{total} = The total energy consumption of a truck on a given road link.

E_{diesel} = The total diesel consumption of a truck on a given road link.

E_{motor} = The total electrical propulsion energy consumption of a truck on a given road link.

E_{regen} = The total electrical regenerative brake energy consumption of a truck on a road link.

We observe two distinct scenarios.

Scenario 1: If SOC > 20%

If $E_{total} \geq 0$ and

If $E_{electric} \leq 0$ then $E_{total} = E_{electric}$

Else $E_{total} = E_{electric} + E_{diesel}$

If $E_{total} \leq 0$

Then $E_{total} = E_{regen}$

Scenario 2: If SOC < 20%

If $E_{total} \geq 0$ then $E_{total} = E_{diesel}$

Else $E_{total} = E_{regen}$

3. Case study

3.1 Physical characteristics of the truck

FPInnovations, in collaboration with its industrial partners, developed the concept of an electric tractor semi-trailer to support the forest transportation industry's efforts in reducing GHG emissions. Unlike traditional designs, this study integrated the electric drive axle into the trailer rather than the tractor. This configuration aimed to improve fuel efficiency in long-haul applications by assisting the tractor during propulsion and regenerative braking. The trailer's electric motor had a peak power of 255 kW. To optimize battery performance, the system ensured that the state of charge (SOC) never dropped below 20%. Additionally, regenerative braking was disabled when the SOC exceeded 95% to prevent overcharging. Since this was a prototype study, economic feasibility and cost-benefit analyses, including factors such as trailer swapping, were not conducted. In forestry operations, where tractors and trailers are often exchanged, a dedicated e-trailer setup may be more viable for fleets with fixed pairings. FPInnovations is currently evaluating its operational flexibility and economic trade-offs of this system. A data logger was installed on the truck to collect data at a 10 Hz frequency. Some of the physical characteristics of the truck are given in Table 3. While certain parameters remained constant, others were empirically determined using least squares regression.

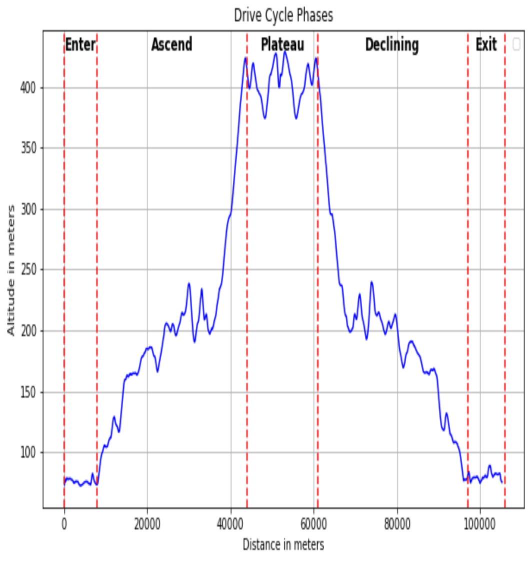
Table 3- Physical characteristics of the prototype hybrid electric truck.

Terms	Value	Symbol	Unit	Description
Mass	54000	M	kg	The total mass of the truck.
Auxiliary Systems	8	Aux	kW	Power to support auxiliary devices and heat ventilation during winter conditions.
Frontal area	8.7	A	m^2	The truck exposure area to wind forces.
Overall	44.1%	$\eta_{overall}$	-	The overall efficiency of the hybrid electric

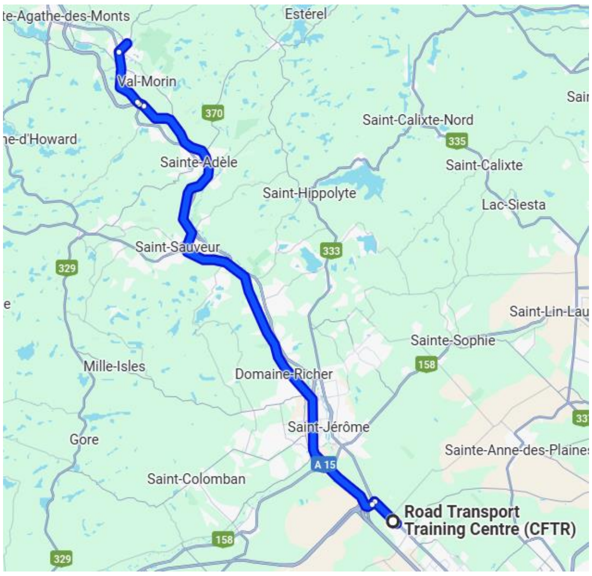
efficiency				truck was found by solving a least square problem.
Aerodynamic Drag	0.73	C_d	-	The drag coefficient of the truck. Found by solving a least square problem.
Rolling resistance	7.9	M	Kg/ton	The tire rolling resistance. Found by solving a least square problem.

3.2 Drive cycle description

The truck was tested at the Le Centre de formation du transport routier de Saint Jérôme (CFTR), situated on the outskirts of the Greater Montreal Metropolitan Area. The road material was paved cement asphalt. Seven trials were done between 13th February and 1st March 2023. Data was recorded between 7 AM and 1 PM for each day of the testing. The weather conditions comprised mostly days with heavy snow and the other being clear skies. The overall roundtrip distance was 105 km. To simplify the analysis, the cycle was divided into five phases, as shown in Figure 3. A primary use of the e-trailer was engaging in regenerative braking when going downhill. During this phase, the e-trailer functioned as a kinetic energy recovery system (KERS) while also assisting propulsion. The parallel configuration assisted the diesel engine with minimum modifications. A comparative study of different KERS technologies can help quantify the best braking strategies. This aspect is beyond the scope of this study. Table 4 below shows the savings accumulated during each of the driving phases.



(a) The altitude profile.



(b) The route trip.

Figure 3- The drive cycle and the driving phases (Surcel and Mercier, 2023).

Table 4 - The comparison of regenerative braking for each driving phase.

	Entering	Ascending	Plateau	Decline	Exit	Total
Energy (kWh)	2.21	3.28	5.58	14.92	6.496	32.486
Distance (km)	8	36	17	36	8	105

3.3 Application of the proposed model

Using the proposed methodology, the model is tested on two drive cycles to assess the suitability of hybrid vehicles for mountain roads. These simulated drive cycles represent a hilly road profile frequently traveled by heavy trucks in Quebec, as shown in Figure 4. The slope profiles were obtained from Google Earth. The route was mapped and exported to GPS Visualizer, a tool used to generate customized maps from geographic data (GPS Visualizer, 2024). Road speed limits were determined by referencing route details, with interstate highways having a speed limit of 100 km/h. The selected drive cycles include both flat and hilly terrains, representative of the routes used for timber and lumber hauling. The analysis considers a truck with three different battery capacities, with an assumption that a larger battery reduces the available payload, as shown in Table 6. Energy consumption savings, expressed as a percentage, are used as a Key Performance Indicator (KPI) to compare the efficiency of the different battery capacities. Table 5 provides the detailed characteristics of the drive cycles.

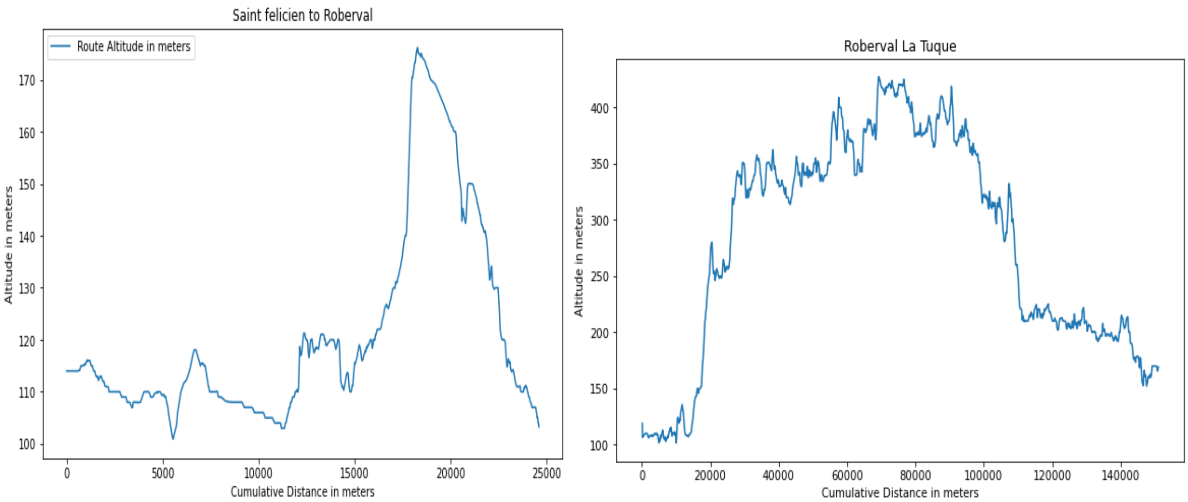


Figure 4- The two simulated hilly drive cycles from the province of Quebec.

Table 5- The simulated drive cycle characteristics in Quebec.

Drive Cycle	**Saint Felicien to Roberval**	**Roberval to La Tuque**
Distance	Approximately 25 km one way	Approximately 150 km one way
Max Slope	7.32 %	8.43 %

Min Slope	-3.45 %	-7.97 %
Speed limit	80 km/h	80 km/h
Description	Routes that are used by heavy trucks between sawmills.	Routes that are used by heavy trucks for hauling roundwood.

Table 6- The Truck transported payload weight estimation.

Specific Energy	Battery Capacity	Truck Payload	Battery Weight	Payload loss
0.2kWh/kg	42 kWh	37840 kg	210 kg	0 kg
0.2kWh/kg	70 kWh	37700 kg	350 kg	140 kg
0.2kWh/kg	100 kWh	37550 kg	500 kg	290 kg

4. Results

4.1 Coefficients of the training dataset:

The polynomial was fit to the training dataset to minimize the sum of error squares between observed and expected values. To mitigate prediction errors, an error check was introduced in the analysis to reduce the ill-conditioning in the least squares and improve the coefficient of determination values. The polynomial regression, physics model, and actual fuel consumption results are very close. Table 7 and Table 8 present the results of the trained model.

Table 7 - The coefficients of the training dataset using the measured data.

	Values
β_0	0.0956
β_1	0.0165
β_2	-0.000624
β_3	0.000284
β_4	-6.8E-05

Table 8 - The goodness of fit of the trained regression model.

Parameter	**MAPE**	**MAE**	**RMSE**	**Residuals**	**R^2 (%)**
Value	5.6257%	0.01847	0.02754	0.687	74.71

4.2 Application of the model

Using the above methods to describe the energy requirements using speed and slopes for a profile, we estimate the overall energy consumption, electrical, and regeneration consumption for the simulated drive cycles. The rule-based heuristic ensured the battery SOC never goes below 20%. Mean values from Table 2 were used for obtaining electrical energy consumption for different slope values. The regenerated energy is stored back in the batteries. The final SOC of the battery shows that the larger the battery, the more energy available. Table 9 describes the results and shows that long-distance travel is more suitable for hybrid trucks. Despite the loss in payload, the larger battery capacity shows a better KPI. The methodology helps predict the maximum savings in energy consumption based on road profile information.

Table 9 - Model estimated results for the simulated drive cycles.

Drive Cycle	Saint Felicien to Roberval			Roberval to La Tuque			Description
Capacity	42.00	70.00	100.00	42.00	70.00	100.00	Battery Capacity in kWh.
Regen Energy	5.67	5.67	5.67	77.32	77.32	77.32	Overall energy recuperated through regen braking.
Electrical Energy	11.34	16.55	19.77	73.47	99.67	133.41	Overall positive energy using electric motors in kWh.
Overall diesel energy consumption	265.87	265.87	265.87	1653.57	1653.57	1653.57	Overall energy consumption for the drive cycle in kWh.
Savings in Energy(%)	4.28	6.22	7.45	4.47	6.09	8.08	A KPI to quantify energy savings using an electric trailer.
Final SOC(%)	81.00	84.00	89.00	49.00	54.00	61.00	Final SOC of the battery at the end of the trip.

5. Discussions

This paper introduced a generic data-driven energy consumption model for hybrid electric trucks in long-haul timber transport applications. The object of study was a prototype e-trailer truck designed and developed by FPInnovations. Due to insufficient fuel consumption tests, the model applies to a truck running at constant speed on paved roads. Also, the e-trailer was tested only in winter conditions. As a result, there was no measured data to analyze the effects of temperature on the battery State of Health(SoH). A broader study covering different seasons would be valuable to assess the impact of temperature variations on the battery. The physical tests focused on the performance of an electrical trailer on mountainous roads. Thus, no cost-benefit analysis was carried out. Future work could examine the total cost of ownership and return on investment to better quantify the economic viability of such a system. In addition, the measured data was collected from the prototype truck when fully loaded. With a lack of data on unloaded driving conditions, we do not know the electric energy consumption in power assistance mode in such scenarios. We recommend more tests when going unloaded.

6. Concluding Remarks

In this paper, we presented a novel model to describe the energy requirements for hybrid electric trucks operating in mountainous conditions. Using speed and slope as independent variables, we estimate the overall energy consumption of any drive cycle. The benefit of the methodology is one can estimate the average energy savings using an electric motor, especially when road information is limited. From Table 2, we can select the mean values of electrical consumption, based on a given slope value. Inaccurate road slope information is currently the main impediment to accurate energy estimations. We contextualize the findings from the physical tests to other routes. We test the methodology for two routes. Long-distance driving is better for hybrid trucks due to numerous up-and-down hills. The simulated drive cycles show energy savings from 4.28% to 8.08%. More research is required to study hybrid truck operations on gravel road conditions.

7. Acknowledgments

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