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Simulation platform of electric road systems – a Swedish case study

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Abstract

Electric Road System (ERS) is a key technology to achieve the electrification in the long haulage application due to battery limitations. Before deciding on large scale investments in ERS, it is important to analyse what road segments that benefit the most of such a system. A model of a hybrid powertrain configured as a long haulage truck is developed with the possibility for dynamic charging. Simulations are performed to analyse a region in Sweden where an ERS demonstration is built, to investigate how different ERS configurations affect the energy consumption of the vehicle. It is found that the fuel consumption is decreased by 66% when the full road is electrified, and the travel time decreased by 7%, compared to a conventional vehicle. Simulations also indicate that it is beneficial to only electrify parts of the road and using the battery in the vehicle as energy buffer. Furthermore, different data sources for road elevation and vehicle speed data have been evaluated. It is shown that Google data and speed limit data can be useful for initial studies, but measured vehicle speed data and laser scanned data increase the accuracy in the simulations.

Keywords: Electric Road System; vehicle model; parallel hybrid; road elevation; speed reference; sustainable transport.

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1. Introduction

Electric Road System (ERS) is a technology concept that has the potential to heavily reduce the fossil fuel dependency in the transport system. ERS is defined by dynamic power transfer from the road to the vehicle while the vehicle is in motion, and could be achieved through different power transfer technologies from the road to the vehicle, such as rail, overhead-line (Olsson, 2014a), and wireless solutions (Olsson, 2014b). All these technologies are not yet fully mature (Sundelin, 2016), and what power transfer technology to be used in future ERS is not yet clear. Furthermore, issues regarding the electric grid system needs to be considered in an ERS (Grahn, 2013). These issues are not included in this paper, since the scope here is to quantify the energy savings when there is a technology to dynamically transfer power to the vehicle.

The investments of an ERS is high and it is important to find suitable roads to start introducing the technology. Aspects influencing the suitability are e.g., traffic intensity, elevation, and speed profiles. The focus of this paper is to present a simulation environment that evaluates how different vehicle speed and elevation data sources affect the simulation results, as well as how different ERS configurations affect the energy consumption. The latter includes what road segments that are electrified as well as if there is a maximum electric power the grid can transfer to the vehicle. The evaluation is performed in the region Gävle-Borlänge-Boliden in Sweden. In this region, a 2 km long ERS demonstration site was inaugurated in 2016 (Region Gävleborg, 2017), and there are many industries interested in building an ERS in this region.

2. Truck model

The vehicle considered is a long haulage truck. The configuration of the powertrain is a parallel hybrid electric vehicle extended with the possibility to connect to the electric road. The energy from the electric road is primarily used for propulsion of the vehicle and secondary for battery charging. The model includes dynamics and is forward propagating. Therefore, a model for the vehicle driver is included in the model, as well as a model for the environment and the vehicle itself, see Fig. 1. The vehicle model is divided into the energy management strategy and the different components in the powertrain. Each of these component models will be briefly described in this section. For a more thorough description of a similar model structure, see e.g. Sundström (2014) and Guzzella (2012). The overall complexity of the model is kept relatively simple to keep the simulation time fast, e.g. a road distance of 94 km is simulated in 90 seconds on a standard lap-top.

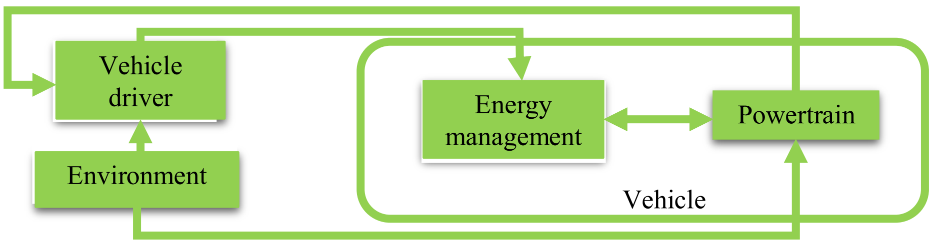

Fig1. Structure of the simulation platform.

2.1. Driver

The accelerator and brake pedal positions are computed in the system denoted vehicle driver. These two signals are computed based on a PI-controller based on the difference in vehicle speed, v, and the reference speed, v_{ref}, given by the driving cycle. The parameters K_p and K_i are parameters and the driver control signal, u_{vd}, is computed as

$$\begin{aligned} e &= v_{ref} - v \\ u_{vd} &= K_p e + K_i \int e\, dt \quad , \quad u_{vd} \in \{-1, 1\} \end{aligned} \tag{1}$$

Functionality for anti-wind-up is implemented in the controller. The pedal position for the accelerator is calculated as

$$\text{accPed} = \max\{u_{vd}, 0\} \tag{2}$$

and the brake pedal position as

$$\text{brakePed} = -\min\{u_{vd}, 0\} \tag{3}$$

The driver is not to handle a clutch pedal or gear selection since a truck with an automatic transmission is considered.

2.2. Environment

In the environment, a driving cycle is loaded including the reference speed v_{ref}, the slope of the road, α, and the availability of ERS as well as if there is a limitation in the maximum power the ERS can deliver to the vehicle. All these signals can vary and are defined as functions of the distance travelled by the vehicle.

2.3. Engine

The fuel consumption is computed based on three look-up tables. First, the friction torque in the engine, $T_{e,fric}$, depends only on the engine speed ω_e and is specified in a look-up table as

$$T_{e,fric} = f_{e,f}(\omega_e) \tag{4}$$

The maximum torque the engine can deliver is also stored in a look-up table as

$$\tilde{T}_e = f_e(\omega_e) \tag{5}$$

The efficiency of the engine is found using a two-dimensional look-up table denoted $f_{e,e}$ where the delivered torque, T_e, is an input signal as

$$\eta_e = f_{e,e}(\omega_e, T_e + T_{e,fric}) \tag{6}$$

Transients in the engine torque results in increased fuel consumption. This is here modelled as a factor, γ_f, used in the fuel consumption computation. The factor is modelled as a look-up table $f_{e,t}$ as

$$\gamma_e = f_{e,t}(\frac{d}{dt}(T_e + T_{e,fric})) \tag{7}$$

The fuel flow is computed as

$$\dot{V}_f = \frac{(T_e + T_{e,fric})\,\omega_e}{\eta_e(T_e, T_{e,fric}, \omega_e)\rho_f H_l}\gamma_e(T_e, T_{e,fric}) \tag{8}$$

where ρ_f is the fuel density and H_l the lower heating value of diesel.

2.4. Clutch

A model for the clutch is included in the powertrain model. A control signal, u_{clutch}, is computed based on the accelerator pedal position, speed of the wheels, and whether a gearshift occurs. The clutch is modelled to be either fully closed or fully open, i.e. there is not any slip implemented in the model. The delivered torque from the clutch is computed by

$$T_{clutch} = T_e u_{clutch}, \quad u_{clutch} = \{0, 1\} \tag{9}$$

2.5. Gear box

The considered gear box is an automatic manual transmission model. The overall gear ratio is, in addition to the final drive, based on the gear ratios in the split, base, and range of the gear box, ref. The gear ratio in each of these parts of the components are denoted $\gamma_{gb,s}$, $\gamma_{gb,b}$, and $\gamma_{gb,r}$, respectively. The overall gear ratio in the gear box is computed by

$$\gamma_{gb} = \gamma_{gb,s} \cdot \gamma_{gb,b} \cdot \gamma_{gb,r} \tag{10}$$

The gear ratio in the final drive is denoted γ_f and is used to compute the engine speed based on the wheel speed, ω_w

$$\omega_e = \omega_w \gamma_f \gamma_{gb} \tag{11}$$

The electric machine is connected to the conventional part of the powertrain between the split and the base gear ratios in the transmission. There is a gear ratio in the connection between the electric machine and the axle in the gear box denoted $\gamma_{f,em}$, and the electric machine speed is computed by

$$\omega_{em} = \omega_w \gamma_f \gamma_{gb,r} \gamma_{gb,b} \gamma_{f,em} = \omega_w \gamma_f \frac{\gamma_{gb}}{\gamma_{gb,s}} \gamma_{f,em} \tag{12}$$

The delivered torque from the gear box is computed as

$$T_t = T_e \gamma_{gb} \gamma_f \eta_{gb}(\text{gear}) + T_{em} \frac{\gamma_{gb}}{\gamma_{gb,s}} \gamma_f \gamma_{f,em} \tag{13}$$

where η_{gb} is the efficiency of the transmission and is dependent on the selected gear.

The gear selection strategy is depending on ω_e and the accelerator position. Two look-up tables are defined, one for up-shifting and one for down-shifting, to state at what engine speed an up-shift and down-shift, respectively, should be performed. A gear shift is implemented to take a predefined time where no torque is transferred from the engine to the wheels.

2.6. Electric machine

The delivered torque from the electric machine is modelled to be the requested torque from the overall energy management, i.e.

$$T_{em} = T_{em,req} \tag{14}$$

The maximum torque the machine can deliver is also stored in look-up tables

$$\tilde{T}_{em} = f_{Tem}(\omega_{em}) \tag{15}$$

The speed of the machine, ω_{em} is used to compute the mechanical power from the machine

$$P_{em,m} = T_{em} \omega_{em} \tag{16}$$

and the power losses are given by a look-up table

$$P_{em,l} = f_{em,l}\left(T_{em}, \omega_{em}\right) \tag{17}$$

2.7. Power electronics

The power electronics converts the system voltage to the requested voltage by the controller of the electric machine to achieve the requested torque $T_{em,req}$. However, in this model representation the voltage over the electric machine is not computed since this signal is not needed to find the performance of the machine, nor the energy losses.

The efficiency in the power electronics is modelled to be proportional as

$$\eta_{pe} = \begin{cases} \frac{P_{em,e}}{P_{em,e}+P_{pe,l}} & , P_{em,e} \geq 0 \\ \frac{P_{em,e}+P_{pe,l}}{P_{em,e}} & , P_{em,e} < 0 \end{cases} \tag{18}$$

where η_{pe} is a constant and $P_{pe,l}$ is the power losses in the power electronics. Rewriting the expression results in

$$P_{pe,l} = \left(\eta_{pe}^{-\text{sign}\{P_{em,e}\}} - 1\right) P_{em,e} \tag{19}$$

The power to the power electronics in motor mode is computed as

$$P_{pe} = P_{em,e} + P_{pe,l} \tag{20}$$

2.8. Battery

The current from the battery is computed by the power P_{pe}, the battery voltage U_b, and the current from the grid, I_{grid}

$$I_b = \frac{P_{pe}}{U_b} + I_{grid} \tag{21}$$

The open circuit voltage, U_{oc}, depends on the state of charge, x_{soc} and the battery temperature, γ_b, that is assumed to be equal to the ambient temperature, γ_a. The open circuit voltage is stored in a look-up table

$$U_{oc} = f_{Uoc}\left(x_{soc}, \gamma_b\right) \tag{22}$$

The battery is modelled as an equivalence circuit including the voltage source and a resistance, R_b, connected in series

$$U_b = U_{oc} + R_b I_b \tag{23}$$

The resistance models the electrical resistance in the electrolyte solution [4]. When a battery is charged, some electrons are not transformed into charge due to irreversible parasitic reaction in the battery. This is modelled using the Coulombic efficiency, η_c. This efficiency is in (Lugano-Rojas, 2014) modelled to depend on x_{soc} and I_b, but is here modelled to be a constant, $\eta_{c,value}$

$$\eta_c = \begin{cases} \eta_{c,value} & , I_b \leq 0 \\ 1 & , I_b > 0 \end{cases} \tag{24}$$

The capacity of the battery is denoted Q_b and the computation of x_{soc} is

$$x_{sox} = x_{soc,0} - \frac{1}{Q_b} \int \eta_c I_b dt \tag{25}$$

2.9. Chassis

In the chassis model the forces acting on the vehicle are modelled and the resulting force on the vehicle resulting in an acceleration. The rolling resistance, F_r, Aerodynamic drag, F_d, gravitational forces F_g, the braking torque and the tractive torque are used to compute the resulting torque of the vehicle

$$T_{net} = T_t - T_b - (\underbrace{m_v g C_r \cos(\alpha)}_{F_r} + \underbrace{\frac{1}{2}\rho A_f C_d v^2}_{F_a} + \underbrace{m_v g \sin(\alpha)}_{F_g}) r_w \tag{26}$$

where T_b is the torque from friction brakes, m_v the vehicle mass, g the gravitational constant, C_r a constant, ρ the air density, A_f the frontal area of the truck, v the vehicle speed, C_d a constant, m_v the vehicle mass, and r_w the wheel radius.

The inertia of the powertrain is computed based on the inertia in the engine, J_e, the gear box, J_{gb}, the electric machine, J_{em}, and the wheels, J_w. The inertia is used in the computation of the vehicle acceleration and is compensated for the different gear ratios in the transmission

$$J_{tot} = J_e (\gamma_{gb}\gamma_f)^2 + J_{gb}\gamma_f^2 + J_{em}\left(\gamma_{f,em}\frac{\gamma_{gb}}{\gamma_{gb,s}}\gamma_f\right)^2 + J_w \tag{27}$$

The acceleration of the vehicle is computed by

$$a = \frac{T_{net}}{J_{tot} + m_v r_w^2} r_w \tag{28}$$

and the vehicle speed by integrating this signal

$$v = \int a dt \tag{29}$$

2.10. Energy management

A heuristic controller is used to determine how much of the requested torque, T_{req}, from the driver that is to be delivered from the combustion engine, the electric machine, and the mechanical brakes. For propulsion, the controller primarily uses electric energy from the grid when this is available. If $T_{req} > \tilde{T}_{em}$, the engine is started to support the machine in the propulsion of the vehicle. When the vehicle can use electric power from the grid, P_{grid}, this energy is primarily used. However, if the maximum power available from the grid, $P_{grid,max}$, is lower than P_{em}, energy is used from the battery. If $P_{grid,max}>P_{em}$ and $x_{soc}<1$, the battery is charged from the grid at a maximum battery current of $I_{batt,chrg,max}$. When $P_{em}<P_{grid,max}$ and $x_{soc}<x_{soc,min}$, the battery is depleted and P_{em} is limited to $P_{grid,max}$. During braking energy is stored in the battery only by conversion of kinetic energy and no power from the grid is used. The magnitude of this battery current, $I_{b,recup}$, can be larger than $I_{batt,chrg,max}$, but if $|I_{b,recup}|<I_{batt,chrg,max}|$ and the grid is available, grid power will be used to achieve a total charging current of $I_{batt,chrg,max}$. In this study $I_{batt,chrg,max}$ represents a charging current of 2C (Reddy, 2011).

When the vehicle is driven on a road where ERS is not available, a charge depletion charge sustain (CDCS) control strategy is used. This means that the vehicle primarily is using the electric machine if x_{soc} is above a predefined threshold. There is a hysteresis implemented in the lower threshold for when to start and switch off the engine in the charge sustain mode to avoid high frequent start and stops of the engine.

2.11. Parametrization

Table 1 presents some key parameter values used in the simulations in Section 3.

Table 1. Key parameters of the truck.

Parameter	Value
Maximum engine power	270 kW
Maximum electric machine power	260 kW
Battery capacity	78 Ah
Battery energy	50 kWh
Maximum charging current from grid	150 A
Battery voltage @ x_{soc}=0,5	630 V
Vehicle mass	60 000 kg

3. Simulations of electric road system

Simulations are performed using different road segments to evaluate the potential of an electric road system. Furthermore, different data sources for the elevation and vehicle reference speed used in the simulations are compared.

3.1. Site

The site considered in the simulations is the region Gävle-Borlänge-Boliden, see Fig. 2. Within this site there are several large industries sending cargo to the Gävle harbor. Trucks are transporting gods in both directions in this region and this leads to that this region has good potential for being a good site for an ERS. A 2 km long demonstration site for ERS is built in the region outside Sandviken (Region Gävleborg, 2017) and many of the industries in the region are involved and supports this demonstration site.

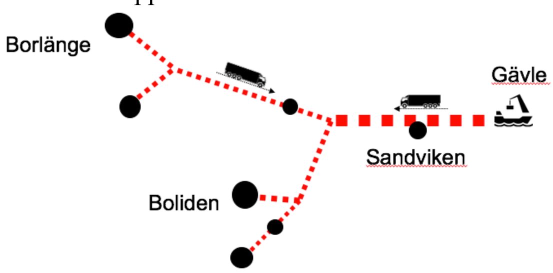

Fig. 2. The region considered in the simulations.

3.2. Speed data

In the vehicle simulations, a reference speed is used as an input signal. The vehicle driver model uses the accelerator and brake pedals to make the vehicle follow the reference speed as close as possible, given the vehicle limitations. Reference speed data used in the simulation model can be collected in different ways. The Swedish national road database includes the speed limit of the national roads. This is therefore a fast and easy way for collecting the reference speed data. However, at real driving the vehicle speed is not equal to the speed limit. To evaluate how this difference affect the energy consumption, the speed profile of a truck driving the road segment Gävle-Borlänge is measured. A user study in a driver simulator has shown that the driving behavior of a truck in an ERS is equal to a corresponding conventional vehicle (Nåbo, 2015), indicating that speed profiles for conventional vehicles also can be used when evaluating ERS. The measured speed is used as the reference speed in the simulation model to investigate how this affect the solution. To more clearly evaluate how the different speed profiles affect the energy consumption, the electric part of the powertrain is not used in the simulations, and only the engine is used for the propulsion. The results are presented in Fig. 3. It can be seen in the figure that the two speed profiles results in a similar simulated vehicle speed at highway driving, but that there are more regions where the speed is decreased and the brake pedal is used when the reference speed is used at low speed driving. The reason for this is that this is at city driving and there are e.g. crossings, roundabouts, and traffic lights. Therefore, the average simulated speed is lower when the measured speed is used compared to the speed limit, 67 km/h and 74 km/h respectively, whilst the fuel consumption is slightly higher using the measured speed data, see Fig 3. It can be concluded that speed limit data can be used as the reference speed in the simulations at highway driving, but measured speed data is important at city driving to get more accurate simulation results

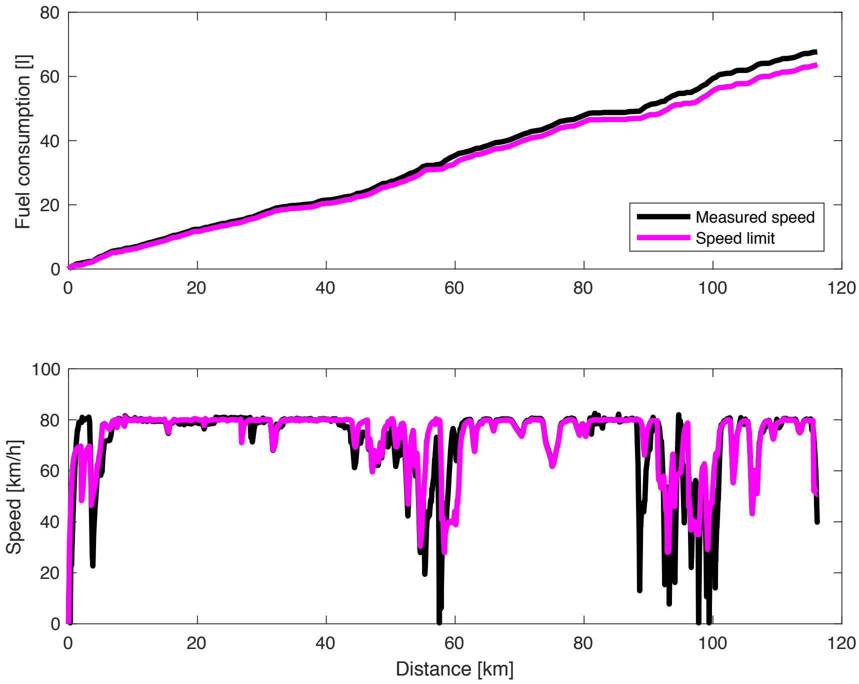

Figure 3: The upper plot presents the fuel consumption when the reference speed in the simulations are based on measurement speed data and speed limit data. The simulated speed profiles are presented in the lower plot for corresponding reference speed profiles. The simulated average speed is 67 km/h when the measured speed data is used and 74km/h when the speed limit data is used. The simulated road is Gävle-Borlänge and a conventional vehicle with only an engine is considered.

3.3. Elevation data

Three different data sources for the road elevation data are compared to evaluate how accurate these are. First, elevation data from the road is collected using laser scanning technique from an airplane. The accuracy is very high, but the cost is also high. Therefore, it is beneficial to use a cheaper data collection approach for initial studies of the ERS potential of different road segments. The second approach is to equip a vehicle with a high accuracy GPS. This has been done and the measured elevation is presented in Fig. 4. This signal is very noisy and needs to be filtered. This is here done using a non-causal butterworth filter, and after this process the elevation profile is similar to the laser scanned data. However, if the laser scanned data would not be available, it would be difficult to know how much the signal is to be filtered. Therefore, this approach is difficult to use to collect elevation data for ERS studies. The final approach is to export elevation data from Google Earth (Google, 2017). It turns out that even though this elevation profile is identical to the laser scanned data, the accuracy is good-enough for initial studies to evaluate ERS in the simulation platform. However, laser scanned data is still recommended for final simulations before recommending a road segment for being suitable for ERS.

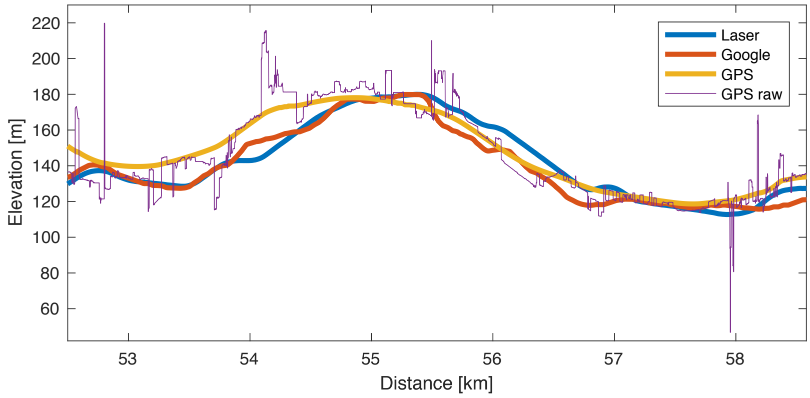

Fig. 4. Elevation data from three different sources. Both the raw GPS data and filtered data are presented

3.4. Energy savings using electric road system

For different scenarios of an ERS are evaluated with the perspective of energy consumption for propulsion of the truck. A conventional vehicle is used as a benchmark. The road considered in these simulations is Gävle-Boliden, and the elevation increases from 16 meters to 176 meters. The technology used for power transfer from the road to the vehicle is not stated in this study. The elevation data used is laser scanned, and the reference speed data is the speed limit data. The first ERS configuration has unlimited electric power available along the entire road and is denoted Case 1. Simulation results are presented in Fig. 5. For this case. In the upper plot the electric energy and fuel energy used for propulsion for every kilometer of the vehicle is presented. This means that the electric energy is the energy to the electric machine. Power can only flow from the grid to the vehicle, and in the second plot this energy is divided into battery charging energy and energy used directly for propulsion. It can be seen that after 34 km of driving the battery is fully charged, which is due to that the battery is charged at 150 A from the grid, as stated in Section 2.11. In Table 2 it is seen that the fuel energy is decreased by 353 kWh (66%), compared to conventional vehicle, whilst the electric energy consumption is 164 kWh. The time saving using the ERS is 338 seconds (7%).

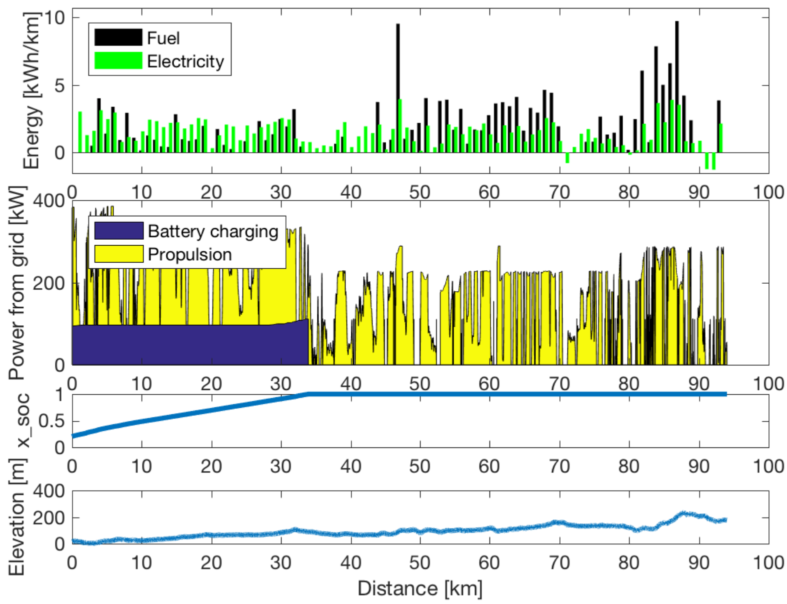

Fig. 5. Case 1: The electric grid is available with no power limits at the entire road.

Corresponding results to Fig. 5 when the grid power is limited to 130 kW (Case 2), i.e. half the power of the electric machine, is presented in Fig. 6. The battery is never fully charged using this limited power since electric propulsion directly from the grid power is prioritised. In Table 2 it is seen that fuel consumption increases slightly and the electric energy decreases compared to the unlimited power case, but the difference compared to the conventional vehicle is still significant.

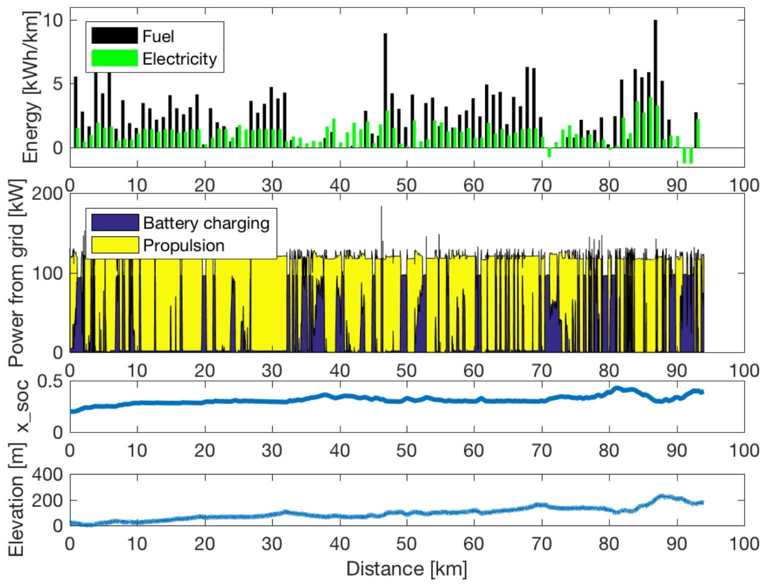

Fig. 6. Case 2: All distance electrified, but the maximum power from the grid is 130 kW.

One case studied, denoted Case 3, is that the electric grid is available for two kilometres and thereafter not available for two kilometres and so forth, see Fig. 7. There is no power limitation. It is shown in the figure that the battery is charged at maximum charging current all the time the grid is available, but the battery is not being charged over time since the battery energy is used when the grid is not available. In Table 2 it is seen that the fuel saving is close to the fuel saving when the grid is available all the time. However, the simulation time increases significantly due to that the battery energy is not sufficient during steep and long uphill driving. The fuel saving per km electrified road is high in this case compared to the former cases. One drawback is that the battery may be depleted due to that there is a high energy flow in the battery with an ERS like this.

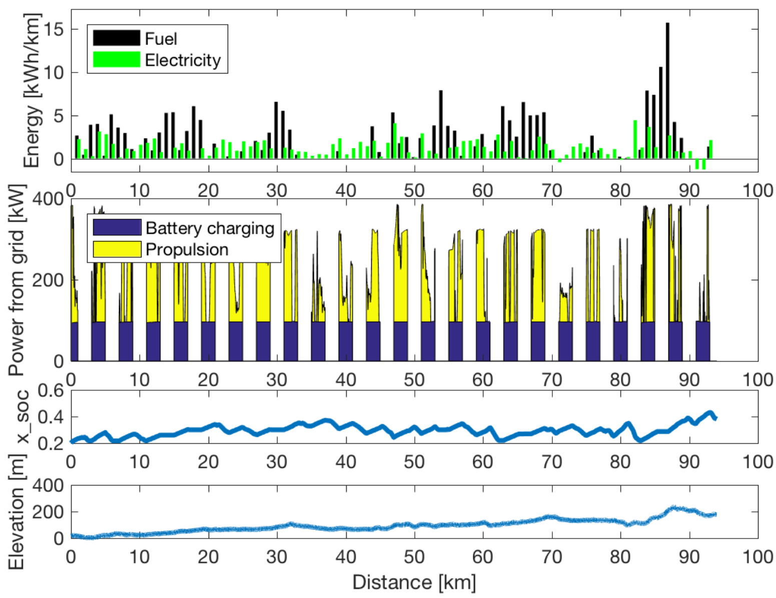

Fig. 7. Case 3: Half distance electrified in sequences of 2 km. No maximum power limit from the grid.

The last considered case, Case 4, is only electrification in the uphill driving at 83 km to 87 km, see e.g. Fig. 7, since the propulsion power is high at this road segment. As can be seen in Table 2, the fuel consumption saving per km ERS is the highest for this case. The time saving is also significant compared to the conventional vehicle case.

Table 2. Energy consumption for different degree of electric road availability. The energy per distance is the energy saving per distance where ERS is available.

Case	Maximum power ERS [kW]	Time [s]	Fuel energy [kWh]	Electric energy [kWh]	Fuel saving @ ERS [kWh/10km]	Electric energy @ ERS[kWh/10km]
Conventional vehicle	-	4586	536	-	-	-
Case 1: ERS available 100% distance	∞	4248	183	164	38	17
Case 2: ERS available 100% distance	130	4309	244	137	31	15
Case 3: ERS available 50% distance	∞	4430	214	142	68	30
Case 4: ERS available 4 km uphill	∞	4457	465	37	175	91

4. Conclusions

A simulation platform for an ERS has been developed, with emphasis of the powertrain of a long haulage truck. The aim of the model is finding how different choices affect the energy consumption of the vehicle. It has been shown that using speed limit data for initial investigations about the ERS potential works better at highway driving compared to city driving due to the many start and stops and more volatile speed in the city driving. Furthermore, laser scanned data is preferably used for elevation data, but due to cost issues google earth data may be good for initial studies. High accuracy GPS data is very noisy in elevation data, leading to problems in how much the signal is to be filtered.

There is no significant change in the fuel consumption if the electric road is available half of the time or all the time if there is enough power available for the battery to be charged at the segments where the grid is available. This is also the case if the maximum grid power is limited to, in this case, half of the power of the electric machine. Most fuel is saved when the electric road is available in the uphill road segment where maximum power of the truck is requested to keep constant vehicle speed. The time for driving the mission is decreased by up to 7% using the ERS compared to a conventional vehicle using the same combustion engine.

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