A TRACTOR INDEPENDENT POWER BASED CONTROL FOR SEMI-TRAILER ELECTRIC PROPULSION




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Abstract

This paper describes a new control approach for an E-Trailer (semitrailer including an electrically propelled axle), being independent of data from the towing truck, and allowing easy flexible adjustment (before or during a trip) through the three involved control parameters. It allows both support and regeneration under driving conditions, and in that way leading to optimal fuel reduction, and with that significant fuel cost reduction, with distinction between city-regional and motorway type of trips. The paper discusses the control concept and the underlying estimation process. The controller uses certain vehicle data, and the sensitivity of the control with respect to uncertainties for some of the most important of these data is considered. The E-Trailer control approach is explored for different driving cycles, including speed and road gradient histories from real trips. It is shown how the choice of control parameters (the control settings) has an impact on the variation in E-Trailer torque request and battery state of charge. Special emphasis is put on the net fuel reduction (no loss of energy in the E-Trailer battery over the specific trip) which is basically the energy gain (and CO_2 reduction) being obtained 'for free'. In addition, the possibly higher fuel reduction at the cost of reduced battery state of charge is discussed, followed by a discussion on the expected fuel cost reduction for different type of trips.

Keywords: Hybrid propulsion, trailer electrification, carbon reduction, E-Trailer

1. Introducton

In the previous HVTT symposium in Brisbane, we reported on semi-trailer electrification to establish hybrid electric heavy good vehicle combinations, also known as E-Trailer (J. A. Aish et. al, [1]). As discussed in that paper, this may be a step towards a situation where the electric trailer may take over the full propulsion, establishing (short range) zero emission transport, and therefore be able to drive with substantially reduced emissions. and be an interesting option for delivering goods in urban areas with minimal impact on the environment. Already from January 2025, 30 to 40 Dutch cities are intending to start with zero-emissions zones. Clearly, shops have to be delivered and commercial vehicles have to do that. The E-Trailer concept corresponds to what is usually aimed for by applying hybrid propulsion. By combining a towing truck with an E-Trailer, large power levels for the diesel engine are avoided by adding support from the E-Trailer based E-axle, whereas efficient (low fuel consumption) conditions and/or braking conditions are exploited to recover energy and charge the E-Trailer battery. As will be shown in this paper, fuel consumption can be reduced in the order of 10 % for regional drive cycle conditions, without loss of energy from that battery over a trip. Hence, these fuel savings are obtained 'for free', not regarding the required investment. And, accepting loss of battery energy, these savings could be raised to 20 % or more.

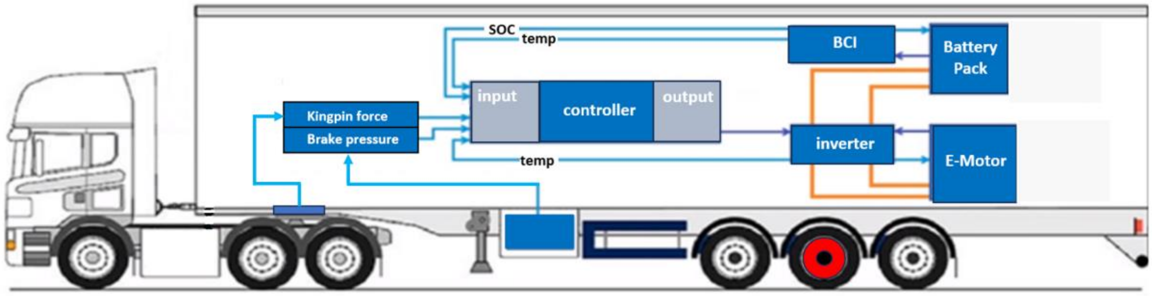

Figure 1.: Self-controlled electrically powered semi-trailer.

With the road transport responsible for over 25 % of the EU CO_2 emissions [2], it is no surprise that new standards have been defined for cleaner vehicles. We quote [2]: Ambitious targets are set to reduce CO_2 emissions compared to 2019 levels by 45 % from 1 January 2030; 65 % from 1 January 2035; 90 % from 1 January 2040 onwards. And, relevant for trailers, as of 2030, specific emissions reduction targets will be in place for trailers (7.5 %) and semi-trailers (10%) compared to 2025. No wonder that various initiatives on E-Trailer are taken such as Trailer Dynamics [3], ZF (Wabco) [4], Schmitz Cargobull [5], VAK [6], the YDrive initiative [7] and the Kraker E-Trailer (J.A. Aish et. al., [1], [8]). The design the E-Trailer control is usually based on data from the towing truck (Fleet Management System, EBS, driver related data) with possibly data added from the E-Trailer configuration (e.g. SOC). Pushing the throttle indicates the need for support from the E-Trailer, whereas braking suggests a negative the torque request leading to energy recovery. With semi-trailers flexibly exchanged with tractors, this may lead to problems in matching the electrified semitrailer to the tractor. One might also think about longer vehicle configurations such as B-Doubles, where a possible E-Trailer may not communicate with the towing vehicle at all. One might solve this by designing a universal interface specification between truck and semitrailer, as realized as part of the EU ZEFES project [9]. This clearly requires follow-up discussions to get agreement from truck and trailer manufacturers. There is a simpler solution, and that is by introducing a control approach, being independent of the tractor states and parameters, as indicated in figure 1.

This paper presents such a control approach, just using trailer data, allowing for a proper balance between support and energy recovery, resulting in optimal (i.e. maximal) net fuel reduction (no SOC loss) over arbitrary trips (the 'free' part of fuel saving), in combination with possibly extra fuel reduction keeping a minimum SOC level at the end of the trip. In case of braking, the controller will initiate regeneration, quite like other E-Trailer initiatives. Under no-braking conditions, the control is based on the diesel engine power level, estimated through a smart sensor in the kingpin, specially designed for this purpose (described by Hetjes, [9]), monitoring the longitudinal kingpin force between tractor and semitrailer. High power (acceleration, slope-up) corresponds to high fuel consumption, followed by a positive torque request leading to extra support from the trailer. Low power (e.g. motorway cruising, decelerating, slope-down) means relatively low fuel consumption. Only three control parameters are used, allowing flexible adjustment of the control before or during a trip, This is important when the required vehicle data for the power assessment (e.g. driving resistances, axle loads,..) are not accurate, and it will be exploited in trip strategies. The controller design in this paper is part of a larger project CHANGE on E-Trailer development and validation, reported by Kural [10].

This paper is organized as follows. In the next section, the objectives for the E-Trailer research are addressed. In section 3, the research approach is treated including an explanation of the control and the required estimation of the engine power from the kingpin force. Results are presented in section 4 including (virtual) drive cycle analysis and sensitivity analysis, partly based on real driving conditions, including varying road gradient. Operational financial aspects of the E-Trailer are discussed in section 5, followed in section 6 by conclusions.

2. Objectives

It is the **objective** to design an E-Trailer controller, just depending on data from the trailer, including energy recovery (charging the E-Trailer battery) as well as support for the towing truck (discharging the E-Trailer battery), such that maximum fuel reduction is obtained, depending on the type of trip. This requires a reliable estimation of the tractor engine power from the kingpin force, with the control parameters tuned for the specific type of trip. In addition, it is of relevance to consider the financial aspects of the E-Trailer, with emphasis on the operational costs. Fuel reduction without, in average, reducing the battery SOC can be considered as 'free profits'. Fuel reduction at the cost of battery SOC has a price tag. This cost-benefit balance also depends on the type of trip in terms of city-regional and highway.

3. Research approach

The fuel consumption plot in terms of delivered power and engine speed for a diesel engine is shown in figure 2. This plot was derived from the engine characteristics as included in annex 9 in the book by Genta and Morello, but with the fuel consumption reduced with 15 % and the maximum torque with 10 % to match modern vehicle performance, that means with final vehicle fuel consumption below 30 L/100 km, at constant speed with realistic payload.

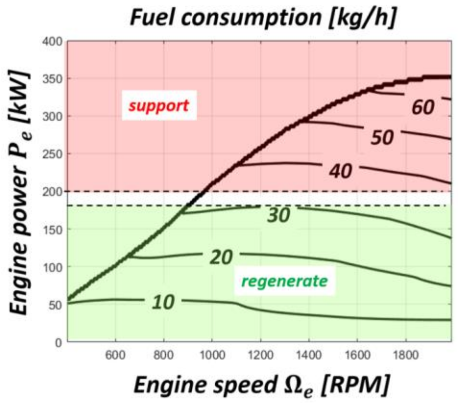

Figure 2.: Fuel consumption as a

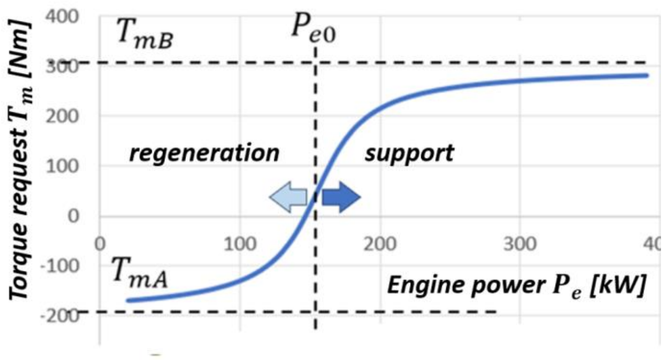

Figure 3.: Proposed control algorithm.

Clearly, when the accelerator pedal is pushed, fuel consumption follows power, and it makes sense to support the tractor when power is high and recover energy when power is low. When the vehicle is braking, brake pressure is changed being observed in the trailer, activating the regeneration mode, with the negative torque request possibly depending on this brake pressure. In the present situation, one level of torque request is chosen for all brake pressures as originally proposed by Jawdat Abo Aish [8], with the exception of low speed conditions, where the torque request is chosen smaller in absolute sense, to avoid too large deceleration under coasting and/or downward slope at low speed. Getting back to the non-braking situation, the proposed control algorithm is shown in figure 3, and mathematically expressed as follows:

$$T_m = \frac{T_{mB} - T_{mA}}{\pi} . \arctan\left(m . \frac{(P_e - P_{e0})}{P_{e0}} \right) + \frac{T_{mB} + T_{mA}}{2} \tag{1}$$

Next to factor m, this algorithm has three parameters, where $T_{mA} (< 0)$ and T_{mB} are the boundaries for the intended torque request and P_{e0} describes the transition from regeneration to support. More regeneration is established by increasing $|T_{mA}|$and/or P_{e0} whereas more support results from larger T_{mB} and/or smaller P_{e0}. The choice of control parameters to arrive at maximum fuel reduction depends on the type of trip being followed. That also allows to adjust these parameters for a certain trip or even during that trip. A second advantage of updating the control is the compensation of possibly incorrect vehicle data being required for assessment of the engine power from the kingpin force F_{KP}. It appears that the slope of the control characteristics at $P_e = P_{e0}$, defined by parameter m, must be bounded to guarantee a unique solution for P_e for a certain value of F_{KP}. The following inequality is found:

$$m \le \frac{\eta_g . \eta_a}{\eta_m} . \frac{m_2}{m_1} . \frac{P_{e0} . r_w}{V . (T_{mB} - T_{mA})} . \frac{\pi}{\tau_m} \tag{2}$$

with tractor and (loaded) trailer masses m_1, m_2, speed V, η_g and η_a being the tractor gear and auxiliary efficiencies, η_m and τ_m the efficiency and ratio between trailer E-motor and E-axle, and r_w the tyre radius. Assuming realistic value ranges for the efficiencies, this inequality is satisfied if

$$m = \theta_m . \frac{1.26}{V.\tau_m} . \frac{m_2}{m_1} . \frac{P_{e0}}{T_{mB} - T_{mA}}$$

with $\theta_m < 1.0$. We have chosen $\theta_m = 0.15$. Note that this makes the control depending on the speed V. The general scope of power based control of the E-trailer force is visualized in figure 4, with kingpin force F_{KP}, resistance forces $F_{resist,i}, i = 1,2$. The tractor drive force F_{drive} is balanced by the longitudinal inertia force $(m_1 + m_2).a_x$ with longitudinal acceleration a_x (assumed to be equal for tractor and trailer), the driving resistance force shared over tractor and semi-trailer (rolling resistance, aerodynamic drag and slope resistance), and the trailer E-axle

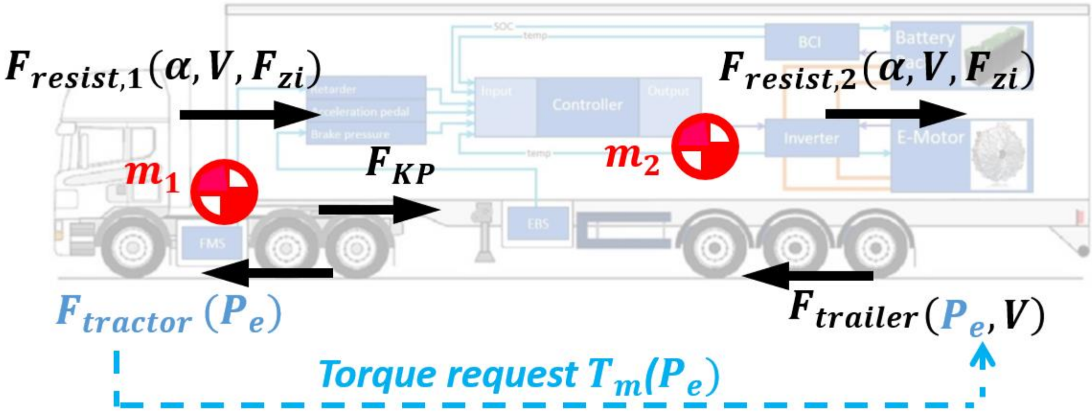

Figure 4.: Driveline model, tractor plus E-trailer.

force $F_{trailer}$. The diesel engine power is transferred to the power $V.F_{tractor}$ at the drive axle, with some efficiency losses in the gear and auxiliaries. The trailer force is directly related to the torque request. The driving resistance includes the rolling resistance (coefficient c_r) based on the axle loads $F_{zi}, i = 1,2,3$, the slope resistance $g.m_i, \alpha$ for road gradient α and acceleration of gravity g, and the aerodynamic drag, expressed as a factor times V^2, being split between a part for the tractor and for the E-Trailer. The share for the tractor (θ) is assumed to be between 0.4 and 0.6. This leads to the following driveline equations for towing truck and semitrailer:

$$\begin{aligned} m_1.a_x &= F_{tractor}(P_e) - F_{KP} - \theta.C_{drag}.V^2 - (c_r + \alpha).(F_{z1} + F_{z2}) \\ m_2.a_x &= F_{trailer}(P_e) + F_{KP} - (1 - \theta).C_{drag}.V^2 - (c_r + \alpha).F_{z3} \end{aligned} \quad (3)$$

For known kingpin force, under non-braking conditions, we have now two equations, with the second one nonlinear, with two unknowns, the engine power P_e and the road gradient α.The various parameters in the equations should be estimated with sufficient accuracy. Sufficient means here that these uncertainties can be compensated successfully through tuning of the control parameters. The set of equations (3) can be solved easily and fast by Newton iteration.

The analysis of the E-Trailer is carried out using drive cycle analysis. That means that known profiles for speed and road gradient are used, based on existing cycles as EUDC (Extra-Urban Drive Cycle), US-C505 (part of the EPA Urban Dynamometer Driving Schedule), and the Highway Fuel Economy Driving Schedule (HWFET). These schedules are given in [12] and presented in figure 5. In addition, trip-data have been collected by monitoring the FMS data during several weeks, while driving with a Kraker trailer, with the trailer manufacturer Kraker, next to Burgers and Nooteboom being partner in the CHANGE project. These trips involved transport of sugar beets from farm to the processing unit, with the vehicle being either unloaded or fully loaded (a total of 50 tonne GVW: Gross Vehicle Weight).

The Matlab model environment being used included the nonlinear engine performance as shown in figure 2 as well as nonlinear efficiency map for the E-Motor efficiency and further supplier specifications for this motor and the battery as well as the driving resistances, also with

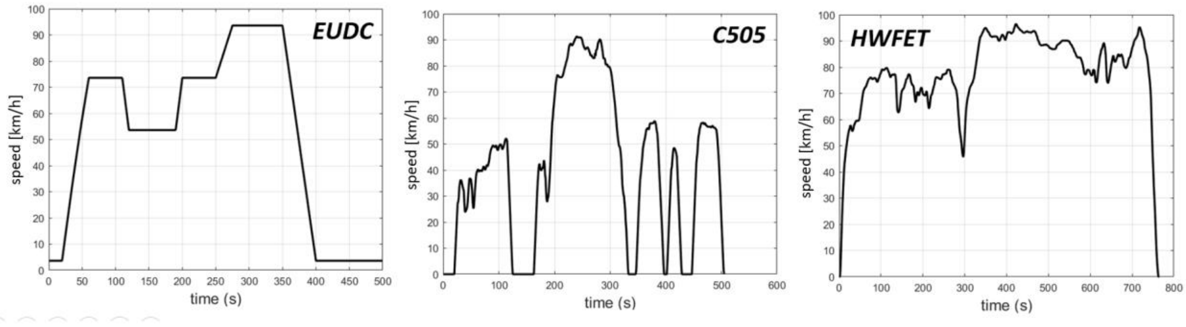

Figure 5.: Drive cycle velocity profiles EUDC, US-C505 and US-HWFET [12].

varying road gradient. A realistic gear schedule was used and axle loads were assumed to depend also on road gradient and acceleration a_x, next to vehicle dimensions and payload.

The choice of control parameters is limited in the sense that a too large torque request may conflict with the maximum allowable torque or power for the E-Motor. Another conflict may come from the maximum charging and discharging speeds for the E-Trailer battery, restricting too fast recovery or support.

4. Results

Let us first explore the effect of changing parameters in terms of fuel consumption during the trip, and the change in state of charge (SOC). We take the EUDC cycle for a flat road, with the vehicle GVW set at 30 tonne. The control parameters are chosen as listed in table 1, also including the resulting change in SOC and in fuel consumption, For the definition of the control parameters T_{mA}, T_{mB} and P_{e0}, please see figure 3 and the explanation in the preceding section. The fuel consumption without E-Trailer control was found to be 2.46 [L]. Observe that for case 1, the change in SOC almost vanishes, meaning that the fuel reduction of about 7.74 % can be considered as a net fuel reduction, i.e. without loss in electric energy.

Case	T_{mA} $[Nm]$	T_{mB} $[Nm]$	P_{e0} $[kW]$	ΔSOC [%]	$\Delta fuel$ $[L]$
0	No control				
1	-200	200	58	0.0056	-0.1903
2	-350	200	58	1.4333	0.0400
3	-200	350	58	-1.6904	-0.4332
4	-200	200	120	1.5156	0.0427

Table 1.: Selected control parameters for first exploration of control behaviour.

Increasing $|T_{mA}|$ results in more regeneration, where the battery is charged with the gained energy, but where hardly any fuel reduction is achieved. For cases 3, the support has increased, resulting in a loss of SOC in combination with fuel reduction of 17.6 %. Case 4 shows a similar result as case 2 with this time the increased P_{e0} leading to increased SOC. Apparently, for every

1.0 % more fuel reduction, the battery SOC is reduced with roughly 0.17 %. In terms of real fuel, this corresponds to 7.0 % SOC for 1 Liter diesel. To understand this in terms of energy balance, consider the situation of a fixed speed on a flat road, and therefore a fixed engine power P_e. In that case, fuel reduction can only be achieved from using the trailer battery energy. The power ratio and therefore the energy ratio between tractor and trailer E-axle is given by:

$$\frac{P_m}{P_e} = \tau_m . V . \frac{T_m(P_e)}{P_e}$$

Hence, this ratio depends on the engine power (and thus on fuel consumption) and vehicle speed, and also on the selected control parameters and the trailer-tractor mass ratio. For a practical drive cycle, speed and engine power vary in time, with the separate contributions building up the final ratio between overall fuel reduction and the SOC-loss.

Note that road gradient has been ignored. Consequently, higher reductions than the (net) fuel reduction of 7.74 % (case 1) can be achieved (at the cost of kWh loss in the battery) as long as the total trip is not too long to deplete the battery, with sufficient initial SOC, and if the trip characteristics are similar to EUDC in terms of speed and speed variation, and with zero road gradient. Suppose an initial SOC of 90 % and a minimum acceptable SOC level of 10 %. Aiming for 15 % fuel reduction, with the total length of EUDC being 500 sec. and an average speed for EUDC of 52 km/h=14.4 m/s, one arrives at a maximum trip length of $80 * 500/(15 - 7.74)/0.17 = 32410\ [s]$ corresponding to about 468 km. This seems like a reasonable trip. Aiming for a reduction as high as 20 % fuel reduction, one would arrive at roughly 277 km. Financial consequences are discussed in section 5.

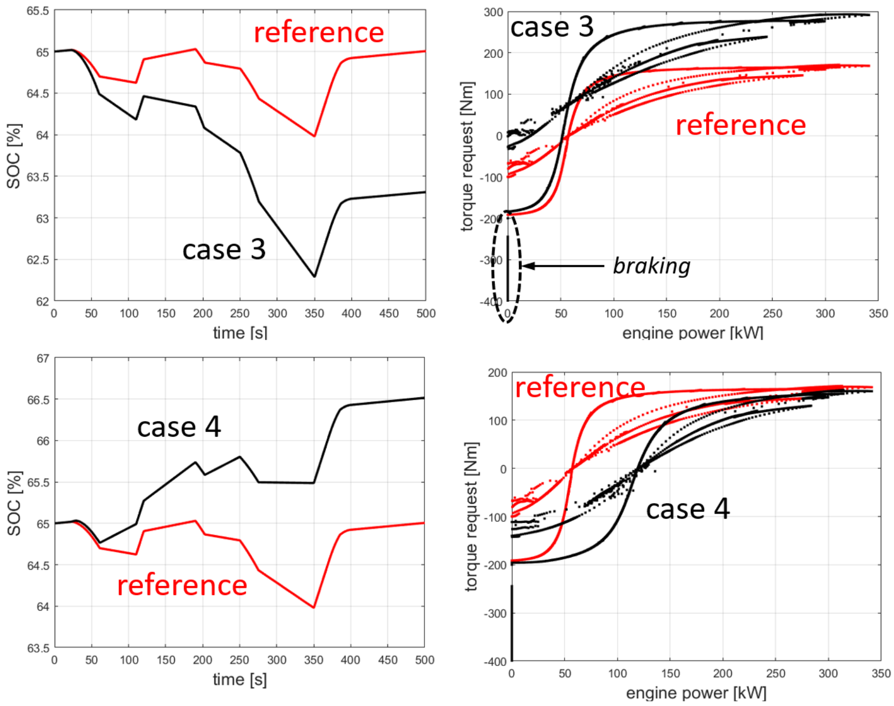

Figure 6.: Results cases 3 and 4, compared to reference case 1.

To illustrate the effect of changing control parameters, we take case 1 as reference. Results for cases 3 and 4 are shown in figure 6 in terms of SOC and estimated engine power vs. torque request. The plots at the right show the control behaviour for the specific settings in terms of its parameters. For case 3, the effect of larger T_{mB} is quite clear, leading to more support with consequences for the SOC. The shift due to change in P_{e0} is clearly shown in the plot for case 4, leading to more regeneration as indicated by the increased SOC behaviour. Note that the control algorithm depends on the speed V, varying for drive cycle EUDC.

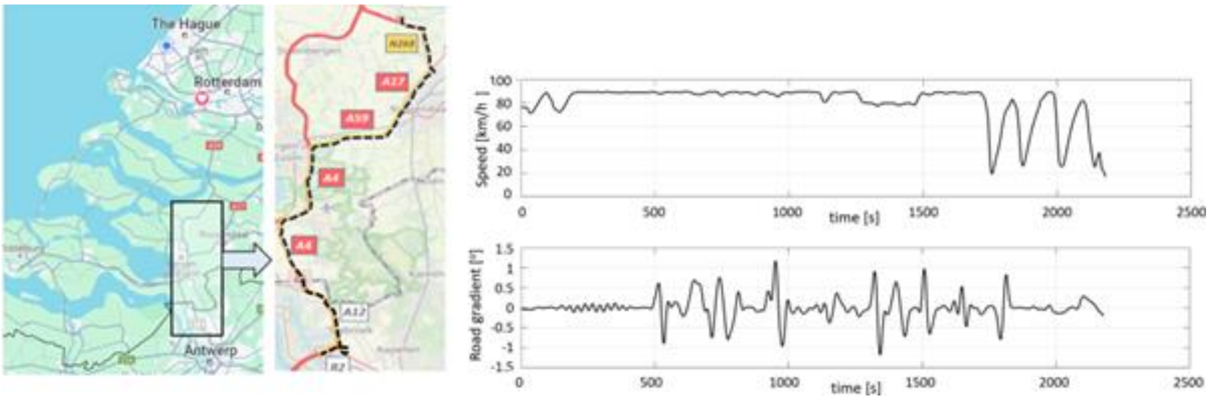

Figure 7.: Trip, used as drive cycle.

Next, sensitivity is considered, with emphasis on the parameters, included in underlying equations (1) – (3). This analysis is based on drive cycle analysis for a real trip with a conventional fully loaded Kraker trailer (50 tonne vehicle mass), as shown in figure 7, with indication of vehicle speed and road gradient. The controller settings were chosen as $(T_{mA}, T_{mB}, P_{e0}) = (-200, 200, 100)$, serving as a reference control. Initial SOC was set at 65 %. The fuel being saved under reference control conditions amounted about 1.9 [L] corresponding to 10.71 %, at the cost of a decrease of slightly more than 6.6 % in SOC. The results of the drive cycle analyses are listed in table 2 with again $\Delta fuel$ expressing the fuel reduction and ΔSOC the effect on battery energy. The first row shows the uncontrolled values. The second row includes the reference control results. Various uncertainties have been examined including an erroneous trailer mass, an incorrect trailer CoG position (rearward shift), a too low tractor mass, and an error of 500 [N] in the kingpin force. The kingpin force could be affected under severe cornering conditions, road disturbances, suspension vibrations etc. Local errors, which may exceed the level of 500 [N], that means for a certain location for only a small part of the route, will have a minor effect on the overall fuel consumption. A major uncertainty is related to the driving resistances, being required in the estimation of the engine power, through equations (3). It turns out that errors in these resistances have only a minor impact.

uncertainty	SOC [%]	$fuel$ [L]	ΔSOC [%]	$\Delta fuel$ [L]	$\Delta fuel$ [%]
none	65	17.59	0	0	0
reference	58.37	15.72	-6.63	-1.88	-10.71
m_2: - 10 %	59.48	15.89	-5.52	-1.70	-9.66
trailer CoG: + 1 m	61.50	16.20	-3.50	-1.39	-7.92
m_1: - 10 %	58.09	15.67	-6.91	-1.92	-10.92
F_{KP}: + 500 N	53.17	14.92	-11.83	-2.67	-15.17

Table 2.: SOC and fuel for parameter uncertainties.

The deviations in SOC and fuel are most significant when the trailer CoG has been changed and for a disturbance (continuously throughout the trip) of the kingpin force. A limited effect is shown for underestimated trailer mass.

Trips with the trailer being empty or fully loaded will cause no problems in estimating trailer mass. For trips with delivery at different addresses, the trailer CoG will change during the trip, and some estimation of the payload is required, being also part of the CHANGE project.

T_{mA}	T_{mB}	P_{e0}	SOC [%]	$fuel$ [L]	ΔSOC [%]	$\Delta fuel$ [L]	$\Delta fuel$ [%]
−200	200	100	58.37	15.72	-6.63	-1.88	-10.71
−350	200	100	67.02	17.14	2.02	-0.45	-2.58
−200	350	100	47.57	13.90	-17.43	-3.69	-20.95
−200	200	50	49.87	14.41	-15.13	-3.18	-18.08

Table 3.: SOC and fuel for parameter variations.

As suggested before, resetting the control parameters may possibly be used to compensate for these effects. For that reason, the results from table 2 are compared with the results for exact vehicle parameters but for different control settings with these new results listed in table 3, also including the reference case (first row). Next, the results for both tables are presented in terms of ΔSOC vs. $\Delta fuel$ in figure 8. Remarkably, all data seem to lie on the same straight line. The figure confirms that uncertainties can be counteracted successfully by modified control settings. Since the percentage reduction vs. SOC change depends on the specific trip characteristics, the slope of this line will be different for another trip. Finally, the plot indicates a net fuel reduction ($\Delta SOC = 0$) between 4 and 5 %. This relatively low value has to do with the more or less constant speed during most part of the trip. A fuel reduction beyond 20 % is also possible but at the cost of more than 17 % SOC.

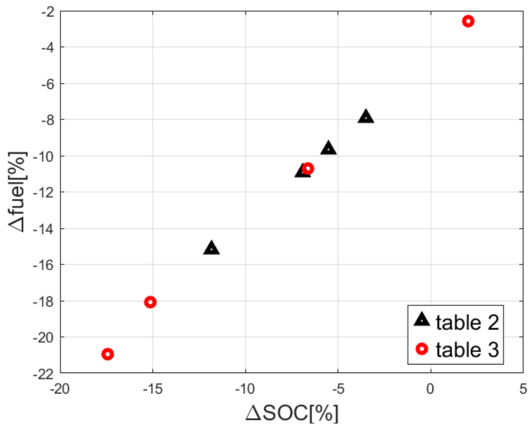

Figure 8.: Graphical representation of data from tables 2 and 3.

Next, consider the drive cycles C505 and HWFET for a flat road and with 30 tonne GVW. A similar plot can be made as in figure 8. Here we use the linearized relationships between ΔSOC and $\Delta fuel$ and carry out a random control setting for both drive cycles (Monte Carlo analysis), see figure 9. Here, the net fuel reductions are found to be -12.1 % and -7.1 % respectively. Apparently, these drive cycles (being much shorter than the previous one) allow more reduction, due to more speed variation. Consequently, there is more gain for the E-Trailer for city-regional trips than for motorway. Observe also that for example 20 % fuel reduction is also possible, but at the cost of about 1.5 % ΔSOC for C505 and 4.5 % ΔSOC for HWFET. In terms of duration, with

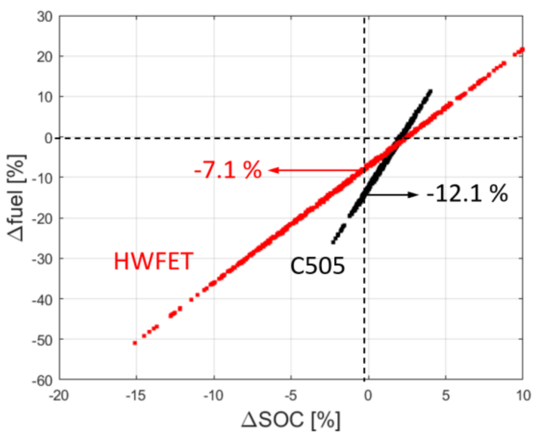

Figure 9.: Variations of SOC vs. fuel for drive cycles C505 and HWFET.

an overall trip characteristics similar to C505 or HWFET, and with available 80 % battery SOC, one would be able to drive almost 7.5 hours with 20 % reduction for the C505 type of trip, and 3.8 hours for the HWFET type of trip. Figure 9 tells us even more than this. The plot has been prepared through random variation of control parameters. That means that, fixing two of these parameters, the net reduction as displayed in figure 9 can be obtained when the third control parameter is used to keep the SOC between reasonable bounds. And this suggests a simple but successful and robust trip strategy.

5. Operational cost-benefit

It is relevant to consider the operational cost benefit. That means the balance between costs in terms of off-line charging the battery and on-line reducing the fuel consumption. Net reduction is 'for free' (except for the E-Trailer investment of course), but additional reduction is not. For the realistic vehicle data and characteristics (taken from [11]), our analysis shows that in the order of $f_{loss,SOC} = 6.3$ % loss in SOC corresponds approximately to a reduction of 1 liter diesel. The total energy content of the battery is taken as $B = 80$ kWh. Our calculation is based on the present Dutch VAT-free costs for electric energy and diesel fuel, $q_{kWh} = 0.26$ [€/kWh] and $q_{fuel} = 1.44$ [€/L respectively. Hence, a comparison has to be made between 0.05 × 80 × 0.26 ➔ € 1.04 and € 1.44 showing there is still a net profit of € 0.40 per liter fuel.

Starting with a desired fuel reduction f_r [%], including a net fuel reduction $f_{r,net}$ with an uncontrolled fuel consumption φ_{NC} [L] for the drive cycle, the financial saving is calculated from:

$$S = \frac{f_{r,net}}{100} . \varphi_{NC} . q_{fuel} + \frac{f_r - f_{r,net}}{100} . \varphi_{NC} . \left(q_{fuel} - \frac{f_{loss,SOC}}{100} . B . q_{kWh} \right)$$

with the first term related to net fuel reduction and the second term to the fuel reduction at the cost of SOC. For a desired fuel reduction of 20 % for the 500 s. drive cycle C505, with an uncontrolled fuel consumption of 2.87 [L], the savings are € 0.50 for the net reduction part, plus € 0.03 at the cost of SOC, thus in total € 0.53 (for a distance of 5.78 km).

For HWFET, with an uncontrolled fuel consumption of 5.27 [L], this leads to € 0.54 for net reduction plus € 0.09 thus in total € 0.63. Effectively, the E-trailer leads to a financial saving of 12.8 % for a C505 type of trip (city-regional driving) for trip length up to about 7.5 hours, and 8.2 % for a HWFET-type of trip (mainly motorway) for a trip length up to 3.8 h. For shorter trips, the fuel reduction can be increased, and with that the financial savings.

These simple calculations show that a significant cost reduction can be achieved with an E-Trailer, with a significant part arising from the net reduction. That suggests that first of all emphasis should be on the net reduction, confirming the trip strategy discussed in the previous section. When off-line charging is accepted, one might consider to reduce the boundaries for SOC during the trip, forcing a decreasing SOC, but increasing the cost reduction.

Conclusions

There is a growing interest in electrifying heavy goods vehicle combinations, motivated by the need to make transport more sustainable and reduce its CO_2 emissions, and by forthcoming international standards and regulations. Such regulations also include new targets for the semitrailer, see [2]. So far, truck manufacturers focus on the towing vehicle neglecting the trailer, where there is an opportunity to contribute to transport sustainability also by electrifying the semitrailer, and combine this E-trailer with either a conventional tractor within a hybrid concept, or with an electric tractor for range extension.

In this paper, a new electrified (E-) trailer control algorithm is proposed with the following major characteristics and advantages:

- The controller depends only on data from the semitrailer, allowing flexible exchange between towing truck and semitrailer.
- It is shown that uncertainties in parameters, used in the control, can be counteracted successfully by modified control settings.
- The controller is based on the tractor diesel engine power, being estimated through a newly designed kingpin sensor (presented in [9]).
- When the driver is not braking, the control algorithm is described in terms of only three parameters, allowing energy recovery for low power conditions and support under high power conditions. The exact amount of energy recovery and support can be flexibly tuned through the control parameters.
- The control algorithm can be successfully included in a trip strategy, being universal with respect to the type of trip and vehicle service conditions (e.g. payload).

From our analysis, based on Dutch price levels, it can be expected that fuel cost reductions for realistic trip length can be achieved, ranging from more than 8 % under mainly motorway type of conditions, to about 12 % for city-regional trips, based on the analysis using relevant drive cycles. Note that these price levels are lower in most of the EU countries, leading to larger relative cost reductions. Of course, trips will show different variations compared to C505, HWFET, EUDC and even the trip of figure 7, leading to other fuel and cost savings. In addition, driveline characteristics will be different, payload will vary etc. This paper intends to indicate the order of magnitude that can be expected. Data on annual distance, engine efficiency characteristics, typical loading conditions, the extra mass of the E-trailer equipment all have to be accounted for in a final ROI (Return of Investment) analysis, which goes beyond the scope of this paper. In that respect, note that the average fuel consumption for regional conditions exceeds that for motorway, increasing further the saving in terms of fuel and therefore of CO_2 emissions. On the other hand, motorway trips are expected to be considerably longer in distance than city-regional trips.
As a next step, this control algorithm will be implemented in a real semitrailer at the end of 2024, with test results expected during 2025.

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