E-TRAILER, EMISSION REDUCTION BASED ON ELECTRICALLY PROPELLED TRAILER

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Abstract

With the huge challenges of reducing the CO_2 emissions of heavy duty vehicles, electrification and hybridization are some of the key technologies to enable this. Such innovation may be applied to the tractor, but why not in the trailer? Electrifying the semitrailer to support the tractor diesel engine under high power demand conditions, and recovering this energy under low power conditions (braking, down-hill, when the diesel engine runs around the sweet spot) not only helps to cut down fuel consumption, but it offers also improved tractive and off-road capabilities, gradeability, overall braking capacity, and better working conditions for the driver. This paper describes an initiative, taken by Kraker Trailers B.V (supplier of moving floor trailers) to develop an electrically driven semitrailer, resulting in a prototype being presently used in everyday transport activities. This development includes the design of a rule based fuzzy logic controller, delivering the torque request to the trailer electrical system, based on input from tractor and trailer, partly derived through EBS and FMS data. This controller has been verified and tuned virtually as well as through first limited experiments, covering urban, regional as well as motorway driving. The experiments resulted in certain required adjustments where a fuel reduction potential between 15 and 20 % was demonstrated. With the increasing interest in urban zero-emission zones in mind, possibilities of driving the vehicle combination fully electric have been considered, i.e. with a switched-off diesel engine and just using the trailer electric motor. This means that the engine-driven tractor systems and auxiliaries have to be passed by or replaced by electrical systems. Some remarks on this are included in the paper.

Keywords: hybrid propulsion, trailer electrification, carbon reduction, E-Trailer.

1. Introduction

With the automotive industry striving towards clean energy, hybrid electric heavy goods vehicles is one of the answers for the future (Hofman [1], Surcel & Michaelsen [2]). The potential is significant with this technology already being a reality for urban applications with urban driving cycles offering opportunities to recover and recycle braking energy. Considering the total fleet of transport operators, there are over six million medium and heavy commercial vehicles on the European Union's roads, with over 98 % of them being diesel-powered (ACEA, [6]). Recently proposed CO_2 standards [7] by the EU have set 43 %, 64 % and 90 % reduction targets for 2030, 2035 and 2040 respectively, for heavy duty vehicle combinations. And In addition to the ever-stricter emission regulations, from 2025 onwards, several European cities will allow only zero-emission commercial vehicles in their city centres.

With reliable and cheaper batteries, hybridization is an emerging technology for heavy-duty vehicles (Johannesson et al. [3]), being under development from several manufacturers, including DAF Trucks, Volvo, Tesla, Thor, Freightliner, E-Force One, US Hybrid, and Cummins (Verbruggen et al. [4]). For heavy-duty vehicle combinations (tractor-trailers) with most of their mileage in urban and regional areas (short- and medium haul), trailers equipped with electrified components (electric drivetrain) might be a perfect solution for the restrictions mentioned above and certainly a useful step towards full electric driving. Adding an electric drive axle on a semitrailer not only saves fuel and cuts diesel emissions but potentially enhances the truck's up and downhill driving (gradeability)/fuel performance and longitudinal stability. From a logistic point of view, such an additional power source can be ideally used for additional tasks such as cooling, moving floor, remote manoeuvring, etc. Hybrid electric heavy-duty tractor-motorized semitrailer combinations were studied for different duty cycles by Surcel and Michaelsen [10]. In this study, four different heavy duty vehicle configurations were evaluated with respect to vehicle cost, greenhouse gas (GHG) emissions and dynamic performance. These configurations included a conventional combination, a hybrid tractor with a normal or derated engine in combination with a conventional trailer, and a conventional tractor (derated engine) with a motorized trailer. For the last combination, they found fuel reductions around 13 [%] for regional haul, 18 [%] for construction haul and over 28 [%] for off-highway class 8. In general, the configurations with derated diesel engine (including the one with motorized trailer) give the best results. A study by Diba [11] on a combination of a series hybrid tractor drivetrain with a trailer electric drivetrain indicates a reduction of ownership cost in a period of 10 years, compared to conventional combinations. Next to the CO_2 reduction, both studies indicate better tractive and off-road capabilities, and gradeability. Driving safety is increased since the trailer electrification enhances braking capacity and downhill deceleration capability. Longitudinal behaviour of the articulated vehicle is improved, as well as controllability and therefore overall working conditions for the driver. And the tractor ICE can be downsized, leading to further better fuel efficiency.

Kraker Trailers B.V., supplier of moving floor trailers, has taken the initiative to develop an electrically driven semitrailer (E-Trailer) to support the diesel engine, in collaboration with HAN University of Applied Sciences, Van Klink Engineering, RKI Sustainable Solution. The trailer drivetrain consists of an electric motor (maximum torque 400 Nm, maximum continuous power 70 kW), an inverter, a battery pack (capacity 105 Ah), and an Electronic Control Unit

(ECU). HAN was involved in designing the controller. In addition, E-Trailer based purely electrical driving was explored. This paper is partly based on a HAN master thesis report (Jawdat Aish, [5]). Consequently, one has to deal with two power sources, potentially leading to three driving modes, (1) a conventional one with the electric motor switched off, (2) a purely electric one with the diesel engine switched off, and (3) a hybrid one with diesel engine and electric motor working in parallel, either to support the diesel engine at high power driving conditions (accelerating, up-hill) or to recuperate energy (while braking, downhill, during low power demand conditions such as during motorway cruising).

Clearly, under pure electric conditions, all relevant systems in the tractor being diesel-engine driven (e.g. hydraulic steering system, air braking system, the 24 [V] battery system, auxiliary devices) must still function as required. This means that these components need to have an alternative, reliable and sufficient power connection from the E-Trailer. Figure 1 shows the electric drivetrain components (electric motor, inverter, battery pack) of the E-Trailer, the conventional drivetrain of the tractor, and the relevant tractor components that may need to have a power connection from the E-Trailer.

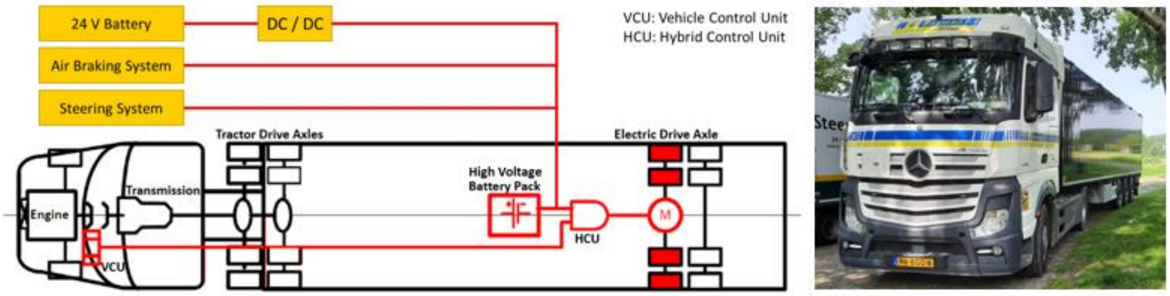

Figure 1.: Layout E-Trailer

The research was aiming at two objectives:

- To establish and validate an E-Trailer controller approach to optimize the tractor-trailer fuel economy (hybrid driving mode).
- To explore the possibility to drive purely electrically based on trailer electrification (pure electric driving mode).

This paper is organized as follows. In the next section, considerations are given with respect to the controller approach and design methodology, resulting in a rule-based Fuzzy design for the hybrid drivetrain power management system (PMS). In section 3, modelling and virtual validation are discussed, followed in section 4 with experimental evaluations and tuning. In section 5, a discussion is included on potential extension to a pure electric E-Trailer drive mode. Overall conclusions are given in section 6, followed by acknowledgements.

2. Controller design

The combination of diesel engine propelled tractor and E-Trailer is a hybrid vehicle (HEV). For HEV's, three main architectures can be distinguished, series, parallel and series-parallel, where the electric machine can operate as motor (propelling the vehicle or at least assisting in this) or as a generator to charge the ESS (Energy Storage System, i.e. the battery) from the ICE or the energy recovered during braking. For each architecture, different configurations may exist. The E-trailer concept is basically a parallel architecture with separate axle torque configuration, with power delivered separately to rear tractor axle and one of the trailer axles. The proper operation mode (supporting the tractor, energy recovery, conventional driving) depends on power demand and driving conditions, aiming at high overall efficiency, optimal recovery and predefined boundaries for the state of charge (SOC) of the ESS. This is to be judged on the basis of the driver commands, internal feedback data (FMS: fleet management system, EBS: Electronic Brake System, additional sensors) and the preset control strategy.

Wirasingha and Emadi [8] and Overington and Rajakaruna [9] reviewed controllers and PMS of HEVs with distinction of rule-based and optimization-based algorithms. Rule based controllers are based on a set of rules (deterministic, Fuzzy), based on the system design, and in general defined based on desirable outputs without prior knowledge of the trip. Optimization-based controllers are based on a cost function, designed and optimized using (historical) driving cycles (global optimization) of applying the actual driving pattern (real-time optimization). An interesting example of the latter approach is given by Zhou et. al. [10] where the battery ageing is included in the cost-function. Higher performance may be expected for the optimization-based approach, but at the cost of portability, computational effort and calibration burden. With the numerous uncertainties in mind regarding driving conditions and tractor/trailer design, the ruler-based fuzzy logic controller (FLC) has been chosen, being relatively simple, robust and allowing the straightforward effective translation of engineers' experience to control rules.

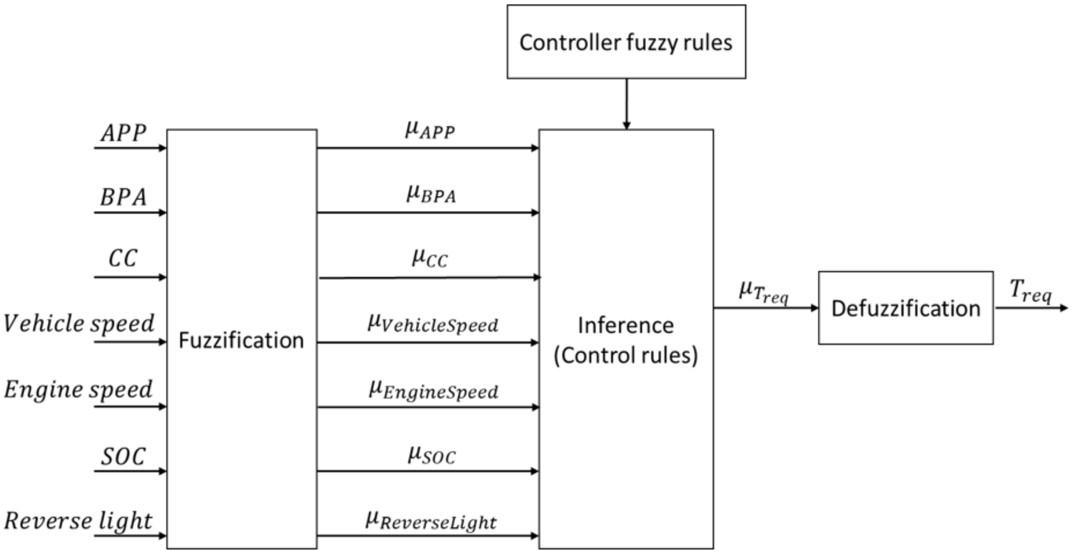

Figure 2.: The E-Trailer control scheme

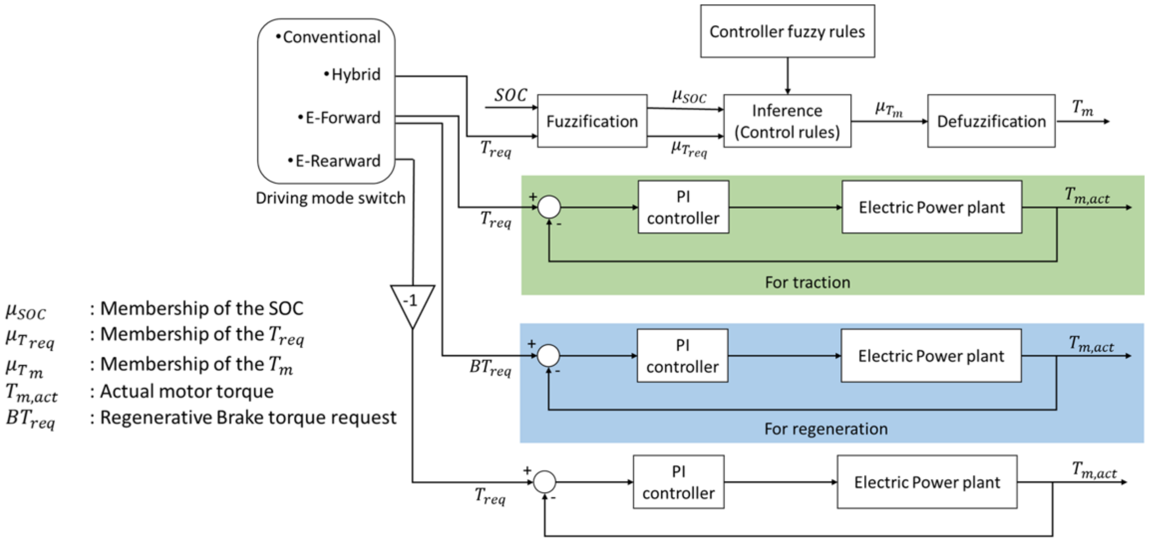

Figure 3.: The rule based fuzzy logic controller

A schematic layout of the FLC is shown in figure 2. The block scheme with indication of the different driving modes is shown in figure 3. The FLC requires seven input variables: the acceleration pedal (APP), brake pressure average (BPA), cruise control (CC), SOC of the ESS, engine speed, and the reverse light signals. The output is the torque request of the electric motor T_{req}, being positive or negative. In general terms, the input signals APP and CC indicate a positive driver's torque request; in contrast, the BPA indicates a negative driver's torque request. The SOC of the ESS signal is needed to avoid overcharging and too extreme discharging the ESS. The engine speed specifies the engine's operation point, to distinguish between situations where fuel consumption is low (sweet spot) and where it is high, with the fuzzy membership functions based on the diesel engine efficiency map. The vehicle speed signal has two functions. First of all, when the driver releases the APP, and the vehicle speed is positive, the T_{req} will be negative, and the electric drivetrain decelerates the vehicle as a retarder function. Secondly, when the vehicle speed is zero and the driver presses either the brake pedal (BP) or the APP in case the neutral gear is selected, the T_{req} will be zero. The reverse light indicates that the vehicle is moving rearward and the T_{req} will be zero. In more detail, a total of 30 (piecewise linear) fuzzy rules have been established where the Mamdani inference method has been used for aggregation of output membership functions.

3. Modelling

The hybrid electric drivetrain has been modelled using the Simscape library in MATLAB, in terms of the subsystems controller, diesel engine, automatic transmission, battery pack, electric motor, tractor and trailer body (differential, axles, wheels, braking system). The components of the hybrid electric drivetrain have been modeled using the datasheets for these components.

A high-level block diagram model is shown in figure 4. The model allows three driving modes, conventional, hybrid and also purely electrically. The input to the controller subsystem are the driving cycle, the driving mode and the vehicle speed (as a feedback). Outputs are accelerator and brake pedal position and the torque request. The diesel engine subsystem transfers the APP into torque, engine speed en fuel consumption (look-up table based on engine torque and angular velocity). Automatic transmission includes two subsystems, the transmission and the shifting logic, where 12 clutches and gear ratios are distinguished. Output is the transmission output power. The electric motor transforms torque request into electric motor torque and speed. The battery pack subsystem simulates the dynamic behaviour of the battery pack during charging and discharging.

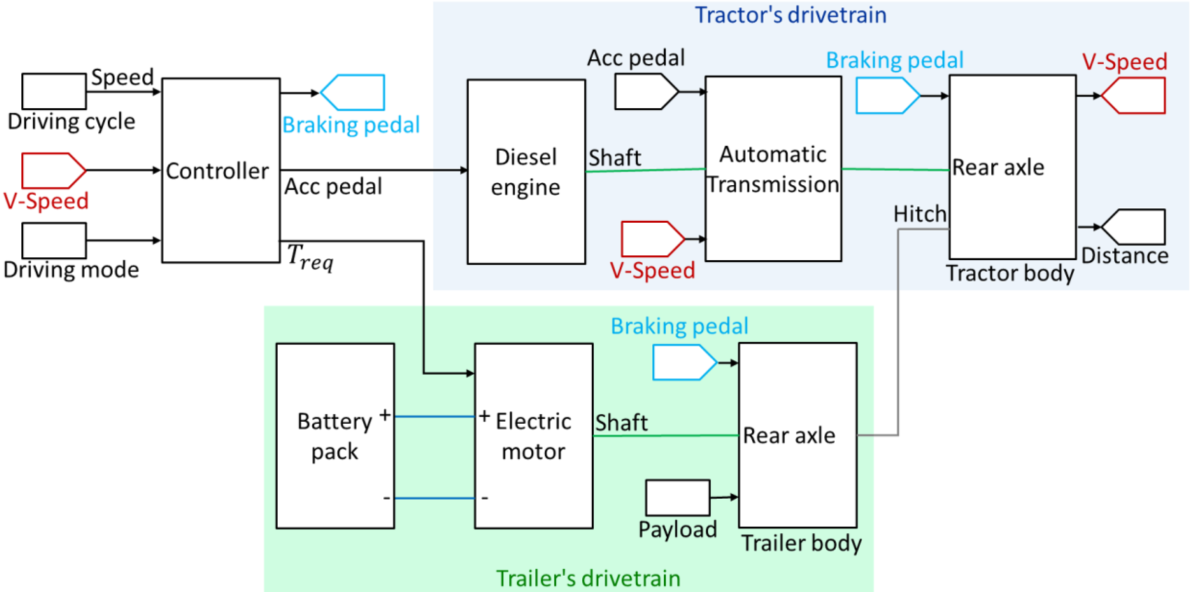

Figure 4.: The high-level block diagram of the hybrid electric drivetrain model.

To validate the model, a drive cycle was derived from test data, based on a special small trip near the Kraker plant. It consisted partly of urban driving, regional driving, part of the motorway, followed by the same parts in opposite order. This trip was also used for a first verification of the impact of hybrid driving, corresponding to conditions which were not exactly reproducible but getting close to that, offering a great advantage in the process of controller tuning.

Three outputs were considered, with the driver controls as input:

- Vehicle speed
- Engine speed
- Fuel consumption

The results are shown in figure 5 where we highlighted the period between 100 and 350 [s]. It starts with motorway, which is left (reducing the speed), some time on a regional road after which the vehicle enters the motorway again. Clearly, speed and fuel consumption follow the experimental data quite well. For engine speed, we see some differences, which is due to the difference in the transmission shifting logic. The truck pulling the prototype E-trailer is equipped with an automatic 12 speed mechanical gearbox with two ranges (high and low) with six gears each. Depending on speed, load and APP, the transmission shifts in a non-sequential manner, whereas the model has a sequential shifting logic. Moreover, it seems that the neutral gear is selected and the diesel engine is idling when the driver releases the accelerator pedal. On the other hand, the impact in fuel consumption is minimal, and the model is considered to be adequate for performing further simulations.

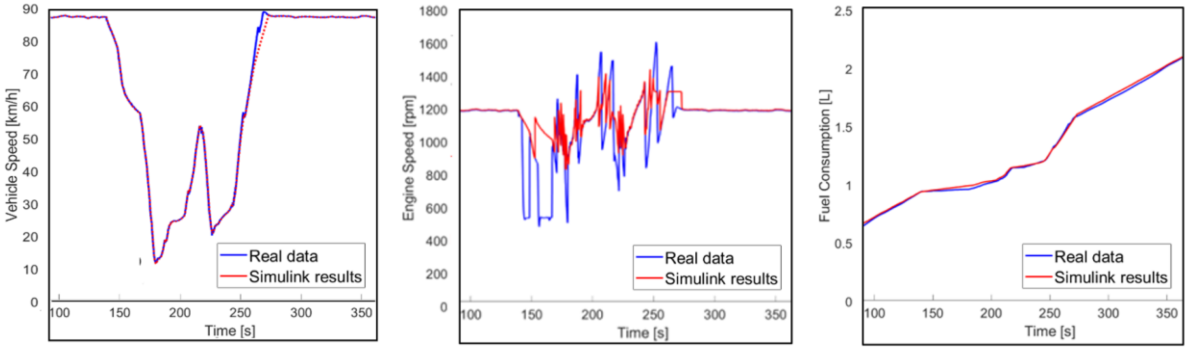

Figure 5.: Comparison Simulink model – driving cycle

To validate the electric drive system in the trailer model, simulations have been carried out for a 13 km city driving cycle with only electric propulsion (no diesel engine), with the trailer fully loaded and the vehicle experiencing a slope of 6 [%] between 730 and 830 [s]. Note that the electric drive system components in the current E-Trailer prototype were aimed for hybrid driving, with the trailer supporting the diesel engine. In order to verify the model for pure electric drive, the sizing of the components were redefined in the model such that a maximum speed exceeding 50 km/hr with a gross vehicle weight of about 50 ton was possible, and the electric motor can drive off on the slope of 6 [%]. The obtained vehicle speed was compared with the model results, and the model appeared to track the driving cycle well, see figure 6. In addition, motor torque and motor speed, following from the model analysis were compared with outcome, being derived theoretically, with both the steady state results and the transitions in between appearing to match well. The energy consumption during the city driving cycle appeared to be around 1,24 [kWh/km], with the SOC dropping from 70 [%] to 46.5 [%]. This suggests in theory a maximum zero-emission trip of about 40 om if 75 % use of maximum SOC

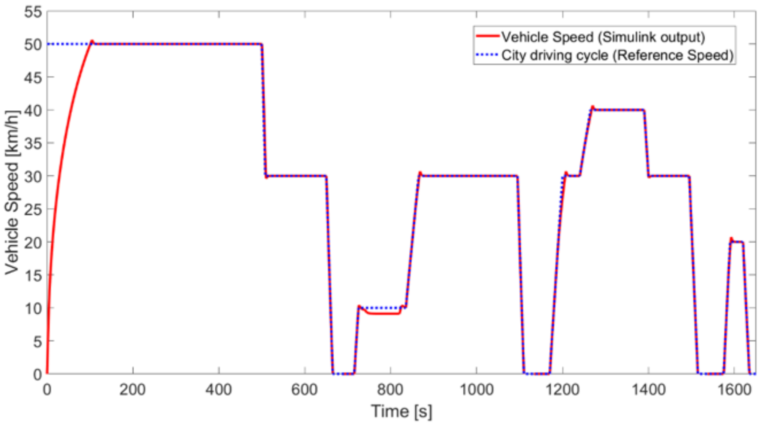

Figure 6.: City driving (input) and the vehicle speed (model output)

is acceptable. For present tractors, during the purely electrically driving mode, the ICE cannot be turned off; it should keep idling to provide power to the relevant tractor systems such as the steering system, the air braking system, and the 24 [v] battery system. In that sense, the above match between drive cycle and Simulink model is theoretical. The situation with the diesel engine idling in combination with electric drive was analyzed and compared to conventional driving. A fuel reduction of roughly 70 % was found. Hence, with present conventional tractors, a significant fuel reduction can already be achieved, be it that this is not fully zero emission.

4. Testing and results on fuel reduction potential

The first set of road tests (with an empty trailer) was used to tune the controller and to find out whether certain problems had to be solved, and issues observed throughout the tests had to be fixed through modification (tuning) of for example the fuzzy logic rules or membership functions. One of these issues was the fact that the actual torque was not able to meet the torque request due to the inverter overheating. The temperature of the inverter was increasing very fast and reaching its limits of $[80^o - 90^o]$ [C] (torque set to zero at 90^o) and taking a long time to cool down, resulting in limiting the electric torque. The problem can be solved by using a separate cooing system for inverter and electric motor (which was done). Another approach could be to take the temperature into account in the fuzzy rules, but that would limit the E-Trailer fuel reduction potential. According to the electric motor supplier, a separate cooling system would improve the motor performance by 40 [%].

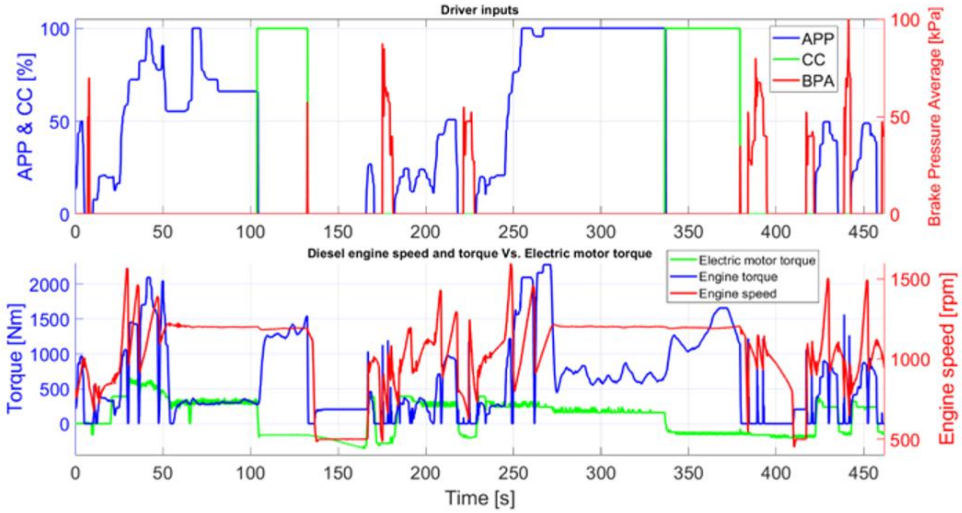

Figure 7.: The driver inputs (APP, cruise control CC, Brake Pressure Average BPA) and the diesel engine speed and torque vs. the actual electric motor torque.

Test results for hybrid driving are shown in figure 7, with the driver inputs (APP, CC, BPA) in the top picture and the resulting electric motor torque, diesel engine torque and engine speed in the lower picture. The fuzzy rules were set such that high APP leads to high torque request for the electric motor. With APP above 60 %, a torque request would be near 800 Nm as a result, but the actual torque doesn't reach that. Below 60 % APP, the fuzzy rules should lead to 400 Nm torque request and also there we see a lower actual torque. Just after 100 [s], the cruise control is switched on and the engine speed is 1220 rpm, which is considered to correspond to high efficiency. The supporting mode is switched to the generating mode. Observe the more or less discrete behaviour of the electric motor torque, being a consequence of the rather sharp transitions between zero, low, medium and high in the membership functions for the fuzzy logic control.

An alternative way to get around the overheating problem (finishing the tests, with the additional cooling system not yet added) is to set the torque request to zero whenever the cruise control is switched on, to give the inverter enough time to cool down. Figure 8 depicts the driver inputs and the torque request for this new version of the FLC showing that the actual torque tracks the torque request now most of the time. Still the motor cannot reach its maximum torque, with the inverter being the limited factor. Using this new version of the FLC, the fuel consumption reduced by 19.9 %. In addition, 6.6 % was saved in time as a result of better acceleration performance. The SOC of the ESS dropped 2 % during the 450 [s] of the trip. Please note that these results correspond to a short single trip.

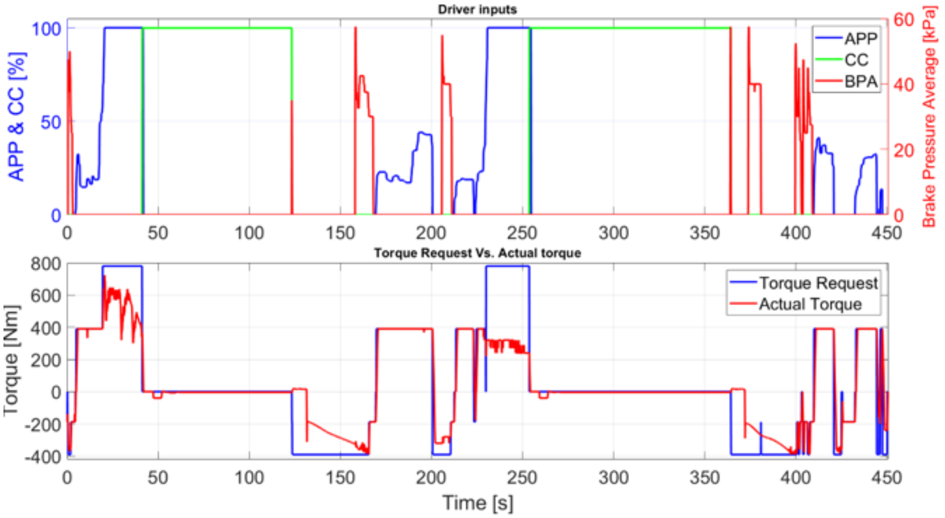

Figure 8.: Driver inputs and the FLC torque request vs. the motor's actual torque.

5. Some remarks considering pure electric driving

As mentioned before, all auxiliaries in a heavy-duty vehicle (e.g. power assisted steering system, air-brake system, 24 [V] battery electric system) are engine driven systems. Moreover, most auxiliary power demand is independent of the engine speed, leading to highly oversized components to meet power demand in worst case scenarios. In order to drive the vehicle combination purely electrically using the trailer-based electric motor for a limited range (typically to enter zero-emission zones), we have to find a way to power the relevant tractor components from the E-Trailer drivetrain. That means for power steering that we may need to have a hybrid electric power steering system (recently presented and used in ZF Lenksysteme and Volvo Trucks, see [12]) or electrical hydraulic power steering (EHPS) systems where the hydraulic pump is decoupled from the engine and driven by an electric motor. This system is used in passenger cars, but still under development for heavy-duty vehicles [13]. For use of an EHPS in the E-trailer, we need a high voltage to cope with the high power demand. The E-trailer has a high voltage battery pack, capable of supplying sufficient power. In addition to the power demand there is also a packaging challenge, and we may expect flow and pressure losses due to the distance between trailer and tractor which have to be considered.

Considering the air brake system, a compressor to produce the compressed air to the system is driven by the engine's crankshaft. In the electric drive mode, the air tank may be filled using an alternative compressed air system, installed at the E-Trailer, and driven by the high voltage battery.

The 24 [V] battery in the truck may be powered from the high voltage battery pack at the E-Trailer through a DC/DC converter during the pure electrically driving mode. The SOC can be controlled through a PID controller.

These suggested modifications mean that the systems are double equipped, which may not be uncommon for hybrid heavy duty vehicles, but the idea of a stand-alone trailer (a necessity from logistic point of view) is gone. Companies will be reluctant to modify their truck. In addition, there are packaging challenges, and most likely there are legal issues to deal with. On the other hand, truck makers are upgrading their electrical system (to 48 [V]) and electrifying the accessory functions being currently powered by the diesel engine. Perhaps that could result in the possibility of driving purely electrically with a switched-off diesel engine in the future.

6. Conclusions and discussion

The concept of an electrically propelled trailer has been investigated to propel the tractor-vehicle combination, as a step towards fully electric driving, or to support the diesel engine as part of a hybrid power system. A rule-based fuzzy logic controller (FLC) has been developed for the tractor – electrified trailer combination (E-trailer) with basically four main objectives:

- To keep the operating point of the diesel engine close to the sweet spot
- To recapture as much braking energy as possible
- To maintain predefined thresholds for the battery SOC
- To improve the acceleration/deceleration performance of the vehicle combination

For validation, a simulation model has been derived also allowing pure electric drive, using the Simscape library of MATLAB to explore the different aspects of the total drivetrain. The model outputs have been compared with real data, gathered through (short) field tests as well as theoretical relationships. Using these field tests, the controller has been tuned, and improvements were suggested (and implemented following this research). The results indicate a potential fuel (and GHG emission) reduction between 15 and 20 [%], compared to the conventional heavy-duty vehicle. Of course, this depends strongly on the driving cycle (urban, regional, motorway) and load conditions (the tests were carried out for an empty trailer), where more field test data is required. The overall efficiency of the diesel engine during the tests was increased with 7 [%] and a time saving in the order of 6 [%] was observed.

Next steps are:

- Collecting and analyzing data from more field tests, with the E-Trailer used in a representative transport environment
- Further improving/tuning the controller on the basis of these field tests, possibly in relationship to the specific practical drive cycle and loading conditions.
- This also includes advanced data science technologies to identify a robust basis for the E-motor torque request for arbitrary tractor design, i.e. making the controller input independent of the tractor using additional signals from trailer added sensors.

The pure electric driving mode of the vehicle combination, with propulsion from the trailer electric system, depends on the electrification of the tractor components being presently driven by the diesel engine. This fits within the innovation trend being observed nowadays, but it will also involve issues with respect to packaging on the trailer, legal aspects, and potential flow and pressure losses between trailer power source and the relevant tractor components. Regarding legal aspects, it is of interest to see whether the EU regulation will allow compensation in payload for the loss of load through the extra weight of the additional components (battery, electromotor, differential) in the order of 500 kg. This has been approved for trucks, but not (yet) for tractor-semitrailer combinations. With pure electric driving, the flexible exchange between E-trailer and arbitrary tractor design including a diesel engine as a single power source is lost. A hybrid tractor design may offer better opportunities.

Acknowledgement

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