FEASIBILITY STUDY OF A STEERED AND POWERED DOLLY FOR AN A-DOUBLE HIGH CAPACITY VEHICLE


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Abstract

This paper summarizes the results of a feasibility study of a steered and electrically driven dolly as part of an A-double High Capacity Vehicle combination. Firstly, vehicle behaviour is assessed in terms of low speed manoeuvrability and high-speed stability, where steering and propulsion control algorithms are proposed to improve the performance. This assessment is done using a multi-body simulation model of the A-double. Secondly the potential fuel and cost savings are determined for the ACEA CO_2 cycle by using a MATLAB model of the through the road hybrid powertrain of the vehicle combination. The optimal power split between the tractor engine and dolly electric powertrain is controlled by an Energy Management Strategy, which is determined by a Dynamic Programming algorithm. Finally all results, including CO_2 emissions and costs, are combined to determine if the steered and powered dolly concept is a feasible and attractive proposition.

Keywords: A-double, dolly, hybrid powertrain, energy management, High Capacity Vehicle, Performance-Based Standards

1. Introduction

1.1 Background

Despite attempts to shift goods transport to other modalities, road transport remains the backbone of goods transport in Europe. Within Europe approximately 75% of the goods transport is done via the road, this figure even rises to 80% for the distribution of goods within the Netherlands as an example, CBS 2015. Considering the increasing share, both in absolute and relative terms, of road transport on the CO_2 emissions within Europe it is clear that the road transport industry has to take its responsibility. Next to improving the vehicle itself, changing the vehicle combination can also result in major CO_2 reductions. This development started in the Scandinavian countries and the European Modular System has been proposed to allow longer (and possibly heavier) vehicle combinations consisting of existing loading modules on parts of the road network. These combinations with an overall length of 25.25 meters are now being allowed in an increasing number of European countries.

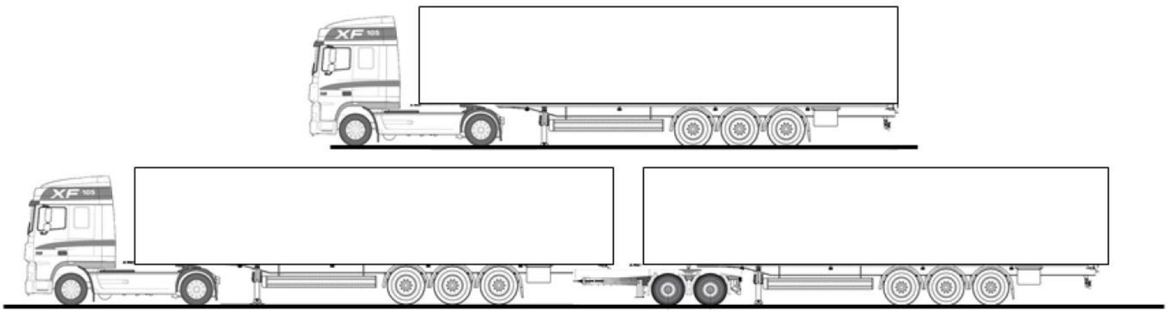

Figure 1 – EU tractor semi-trailer combination (top) and A-double HCV (bottom)

Within Europe tractor semi-trailer combinations have by far the largest share in the long-haul transport sector. Therefore the most obvious high capacity vehicle (HCV) configuration is a combination of a tractor and two standard non-steered semi-trailers interconnected by a dolly, as shown in Figure 1. The overall length will be approximately 32 meter and experiments have already been executed with this vehicle combination in Sweden and Finland, e.g. the Duo2 project in Sweden (2014). As HCV's are only allowed on a part of the road network, the A-double configuration of Figure 1 can be easily separated into two standard tractor semi-trailer combinations.

Normally a powerful 6x4 tractor will be required to haul the two semi-trailers, but this paper will investigate the use of a standard 4x2 tractor and a driven dolly with its own battery electric powertrain, resulting in a through the road hybrid vehicle combination. Previous work in the field of hybrid powertrains for commercial vehicles has been done for example within the framework of the EU funded Transformers (2017) and EcoChamps (2018) projects. The Belarus truck manufacturer MAZ has displayed a 47 m road train with dollies powered by combustion engines, MAZ (2012). Active steering of the dolly is introduced to minimize the swept path and methods to improve high-speed stability will be investigated. Previous research on active steering of dollies has been executed at Chalmers University, Franz (2015). The results presented in this paper are based on the research of Wouters (2016) and Parfant (2017).

1.2 Design considerations

It is assumed that the Gross Combination Weight (GCW) of the A-double HCV shall not exceed 88 tonnes, which equals the maximum allowed weight of two tractor semi-trailer combinations for intermodal transport. The basic idea is to extend a standard European 4x2 tractor semi-trailer combination with a powered dolly and second semi-trailer. As the total vehicle mass increases considerably, the powered dolly should provide assistance under critical circumstances, for example when accelerating or driving uphill. Furthermore the manoeuvrability of the existing tractor semi-trailer should not be negatively affected by the additional dolly and semi-trailer. These goals can be achieved by minimizing the drawbar forces from the dolly to the first semi-trailer and the introduction of a path following dolly steering system that makes the 5th wheel of the second semi-trailer track the same path as the 5th wheel of the tractor.

Since the dolly is equipped with a steering and propulsion system, it becomes a "mini"-tractor and can be used for autonomous applications like e.g. auto-docking at warehouses in the future as well. Following this vision, the dolly is designed to meet requirements normally applicable to a tractor. For example, the dolly powertrain should have a minimum power output of 5 kW/t and it must be capable of starting on an up-hill gradient of 12 %. It also has to meet the EU and Dutch axle load, dimension and swept path legislations, stated in European Commission (2015), European Commission (1997) and Overheid.nl (2015).

1.3 Outline of the paper

The outline of this paper is as follows: Section two analyses the dolly steering, propulsion and dimensions. Section 3 deals with vehicle dynamics, the steering and propulsion controller, maneuverability and high-speed stability. Section 4 describes the optimisation of the hybrid powertrain, a prediction of the fuel consumption and costs of the hybrid A-double. Section 5 presents the conclusions and recommendations for future research.

2. Dolly design

2.1 Steering and propulsion

The first step for the dolly design is to determine its dimensions and component positions. Initial calculations show that the dolly should have at least two axles to meet the axle weight legislation when towing a fully loaded semi-trailer. Two design concepts for this two-axle dolly have been evaluated. The first design is a 4x2 front-wheel steered dolly with rear wheel propulsion. The second concept is a 4x4 four-wheel steered, four-wheel drive dolly. Both designs are shown in Figure 2.

For the 4x2 dolly two steering systems are evaluated: a drawbar steering system and a mechanical linkage steering system. In the drawbar steering system design, the front axle is rigidly connected to the drawbar, such that the front wheels are steered when an articulation angle is present. In the mechanical linkage steering design, the front axle is mounted to the chassis and a mechanical linkage between the drawbar and the dolly's front wheel hubs makes the wheels steer, similar to the system patented by Krone (2009). Both steering systems have two yaw articulation points. In both designs, the first and second articulation point are positioned at the pin coupling and end of the drawbar respectively.

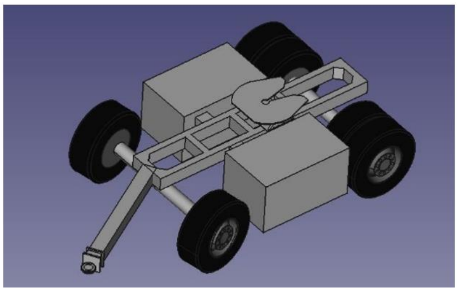 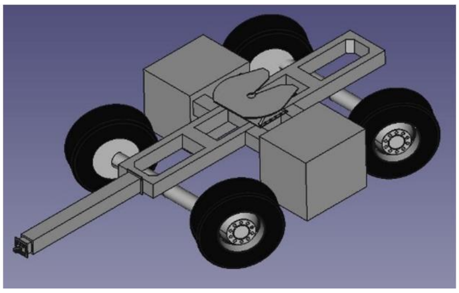

Figure 2 – 4x2 dolly design with mechanical linkage steering (left) and 4x4 dolly design with four wheel steering (right) to be used in the A-double HCV

For the 4x4 dolly two concepts are considered. The first 4x4 dolly concept is rigidly attached to the first semi-trailer, like a c-type dolly. The second 4x4 dolly is connected to the first semi-trailer with a pin coupling, as shown in Figure 2 on the right. Both 4x4 dolly steering systems are independently 4 wheel steered. For both the 4x2 and 4x4 concepts an optimization of drawbar-chassis articulation positions and/or steer ratios has been performed. Roundabout simulations for an outer radius of 12.5 meters show a swept path of 9.40 meter for the 4x2 and 6.78 meters for the 4x4 dolly. The swept path of the 4x4 dolly is only 1.2 % larger compared to a tractor semi-trailer combination.

Furthermore the EU legislation in European Commission (2015) states that 25% of the GCW should be borne by the driven axles of the vehicle. The maximum axle weight for undriven axles equals 10 t and it is 11.5 t for driven axles. With two driven axles, the 4x4 dolly design has an advantage compared to the single axle 4x2 design. Based on axle loads and swept path considerations it was decided to focus on the 4x4 dolly design.

2.2 Dolly dimensions

The dimensions, axle and fifth wheel locations of the dolly are restricted by several requirements. First of all, the dolly shall fit between two standard curtain side, box or container semi-trailers. Secondly, neither the dolly nor the rearmost semi-trailer shall collide when cornering. Thirdly, the axle weight limits should be met and 25% of the GCW should be borne by the driven axles of the dolly. Fourthly, the dynamic load transfer shall be minimized to maintain the most constant vertical force on the dolly's axles to maintain steerability.

A detailed research on the dolly dimensions has been performed. When cornering, collisions can occur at three locations. These are between the dolly and the rear bumper of the first semi-trailer, between the rear of the first and front of the second semi-trailer and between the dolly and support legs of the rear semi-trailer. Given the worst-case semi-trailer dimensions and the first two requirements, the maximum available space for the dolly is calculated, as shown in Figure 3. The dolly's wheelbase has been maximised to meet worst-case conditions. These conditions include operation with fully loaded semi-trailer, startability on a 15% inclined road and braking and accelerating with maximum accelerations. A large wheelbase also provides more space for the powertrain components and battery pack. The fifth wheel coupling is placed at the center of the dolly wheelbase for an equally distributed vertical tire force. The final dimensions of the dolly are shown in Figure 3.

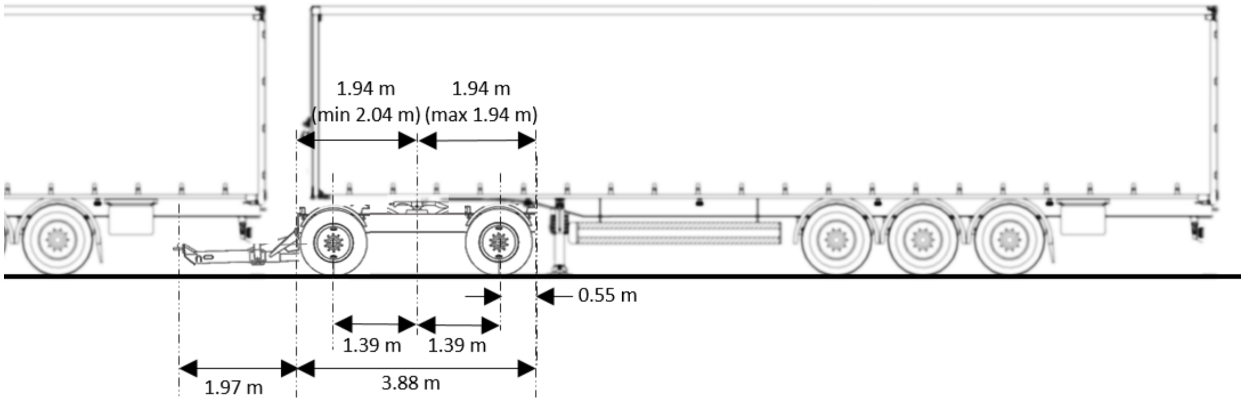

Figure 3 – Final dimensions and locations of the 4x4 dolly design in the A-double HCV

3. Vehicle Dynamics

3.1 Modeling and performance criteria

The A-double's vehicle behavior will be assessed in terms of maneuverability and high-speed stability. One way to assess these criteria is by means of Performance-Based Standards (PBS). A proposal has been made for a European based PBS set by Kraaijenhagen et al. (2015), which uses the Australian PBS as a baseline and extends it with the European legislation. The most important addition is a 360-degree turn maneuver. Within this project, the focus is on two tests which are the low speed 360-degree turn and the high-speed single sine steer input. With these two maneuvers, the following performance criteria are evaluated: low speed swept path, rearward amplification, yaw damping and high-speed off-tracking. The PBS criteria are evaluated using a multi-body vehicle model, which is created using the TU/e Commercial Vehicle Library (CVL). The CVL is based on the SimMechanics multi-body toolbox of MATLAB and models have been validated by Kural (2013).

3.2 Steering control strategy

Four-wheel steering of the dolly is used to increase the maneuverability of the vehicle combination. Ideally both semi-trailers will travel along the same trajectory, which means that the driver only needs to take into account the steering behaviour of the first semi-trailer as he is accustomed to. A path-following steering algorithm will be used. The idea is to store the trajectory of the fifth wheel on the tractor and calculate the required dolly steering angles, such that the fifth wheel on the dolly follow this trajectory too. A feed-forward algorithm is used to calculate the required dolly steering angles with the set point trajectory and current dolly orientation, assuming the required side slip angles are known for the dolly tires.

The set point trajectory is calculated from the trajectory of the tractor. A recent part of the tractor's trajectory is stored in memory, after which a minimization algorithm finds the trajectory point that is closest to the dolly' fifth wheel. Measurement of the tractor and dolly trajectory can be achieved by using for example a GPS sensor and sensors which measure relative rotation between the tractor, dolly and trailers. Interpolation between trajectory points in the vicinity of the closest point is then used to calculate a smooth trajectory set point for the dolly. Since lateral accelerations are small during low-speed cornering, lateral tire forces and hence side slip angles are also small. The assumption of zero side slip is therefore used to calculate the required steering angles for each of the dolly wheels. As a result, the steering angles depend on the (required) yawrate and velocity of the dolly, which can both be determined from the set point trajectory and location of the pin coupling on the first semi-trailer. Note that these steering angles are only correct if the dolly is close to the set point trajectory. This is guaranteed by the algorithm that calculates the set point, provided that the resulting steering actuation is indeed able to keep it close to the trajectory.

Since a single tractor semi-trailer combination shows better high-speed stability than an A-double combination due to its smaller number of articulation points and shorter overall length. The path-following controller is also used to make the dolly copy the movement of the tractor at high speed manoeuvring. It is expected that this will result in better stability if the dynamics of the dolly and last trailer do not significantly reduce the stability of the tractor and first semi-trailer.

3.3 Propulsion control strategy

In order to use the electric powertrain to further improve vehicle dynamics, a propulsion control strategy is needed. In contrast to the steering algorithm, where improvements for both high and low speeds can be achieved by using a single controller, separate propulsion controllers are used for high and low speeds, since the high- and low speed control objectives are entirely different. At low speeds, the goal is to decrease the swept path during the 360-degree turn, which can be achieved by improving the dolly tracking performance and/or by increasing the trajectory radius of the first semi-trailer. It is expected that the radius of the first semi-trailer trajectory will increase when the drawbar forces are zero, since it will travel along the same path as the conventional tractor semi-trailer combination would. The controller therefore aims to create a torque distribution that results in zero drawbar forces, which is achieved by using a feedforward controller that counteracts the predicted forces acting on the fifth wheel coupling of the last semi-trailer. A torque vectoring algorithm distributes this requested tractive force over the four steered wheels.

At high forward velocity, a feedback PD controller generates a yaw moment, in order to make the dolly follow a set point yaw angle. This yaw angle set point is based on the measured tractor yaw angle, which is delayed in time, since the dolly is travelling at a certain distance, and hence time delay, behind the tractor. The idea is that the stability of the A-double increases when the dolly is able to copy the dynamic behaviour of the tractor, since the onset of vehicle instability will most likely occur at the trailing vehicles. This control strategy assumes that application of the resulting controller output does not significantly reduce the stability of the towing tractor itself. The yaw-moment is generated by applying tractive forces of opposite sign at the left and right side of the dolly.

3.4 Low speed manoeuvrability

Low speed manoeuvrability is analysed by performing simulations of a 12.5m outer radius, 360-degree turn. During this manoeuvre, performance is measured by calculating the swept path, which corresponds to the radial distance between the circular trajectory of the innermost and outermost part of the vehicle combination. European regulations require that a conventional truck should have an inner trajectory radius larger than 5.3 m for the test described above. For a left turn, the trajectory travelled by the outer left tire of the last semi-trailer's centre axle is taken for calculation of swept path. The A-double without a steered dolly or semi-trailer(s) is not able to pass this test, since collisions occur between tractor and trailing vehicles.

A comparison of varying simulation cases is presented in Table 1, to show the impact of the steering and propulsion controller on the swept path of the A-double combination. Table 1 shows that the steering controller is able to make the dolly follow a trajectory with swept path comparable to that of a conventional tractor semi-trailer. Even better performance is achieved by activation of the propulsion strategy, which indeed reduces the longitudinal drawbar force. Hence, the steered and powered A-double even complies with European requirements on low speed manoeuvring for conventional transport vehicles.

Table 1- Overview of simulation results for low-speed manoeuvring

Case	Swept path [m]	Long. drawbar force [kN]
Conventional tractor semi-trailer	6.98	N/A
Steering on, propulsion off	7.26	29.2
Steering on, propulsion on	7.01	0.1
Steering angle limited to 45 deg., propulsion off	8.28	-

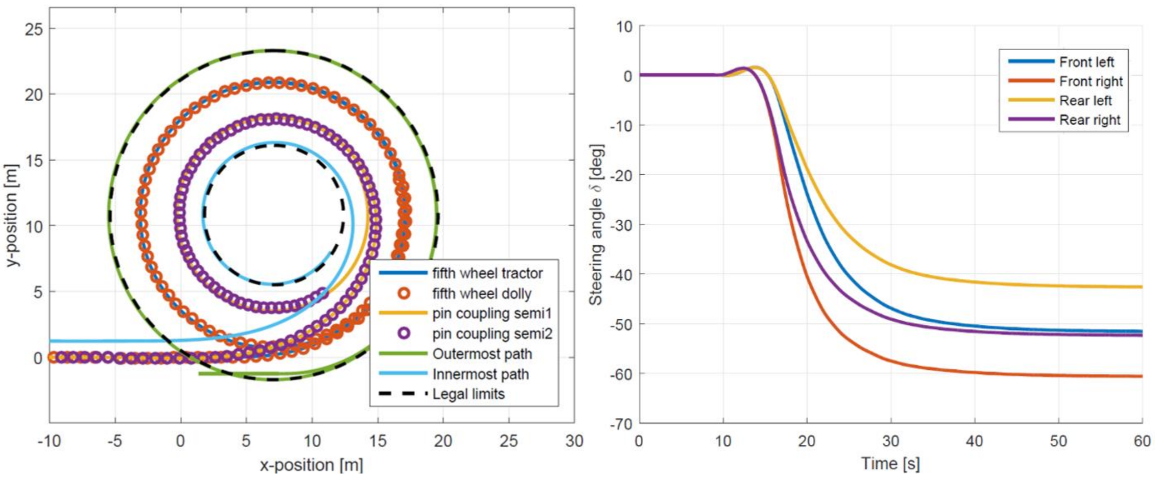

Figure 4 – A-double trajectory (left) and dolly steering angles (right) during simulation of a 360-degree turn

The left graph in Figure 4 shows the path travelled by different points on the A-double combination, during a 360-degree turn with propulsion turned off. The figure confirms that the fifth wheel of the dolly indeed follows the fifth wheel of the tractor, and that the pin couplings on both semi-trailers follow a similar trajectory. The right graph in Figure 4 shows the dolly steering angles. These angles are very large due to the inconvenient orientation of the dolly, which drives towards the outside of the turn in order to follow the tractor. A limitation of the maximum dolly steering angle, caused by for example packaging constraints, will severely limit the performance of the steering controller, as becomes clear from the fourth data row in Table 1.

3.5 High speed stability

High-speed stability of the A-double is evaluated by performing simulations of a single lane-change manoeuvre, as specified in ISO 14791:2000. Here, a single 0.4 Hz sinewave is used as steering input at a forward velocity of 88 km/h. The amplitude of the steering input is chosen such that the lateral acceleration measured at the centre of the tractor steering axle reaches at least 0.15G as required by legislation. Stability is assessed by calculation of the following three performance indicators:

- *Yaw damping:* This indicator describes how fast oscillations in yaw rate and lateral acceleration decay after excitation of the vehicle by a steering input. Hence, a large value is desirable, which is calculated from the vehicle yaw rate response.
- *High-speed off-tracking:* This indicator measures how far the rearmost trailer deviates from the path of the tractor. A small value for off-tracking is desirable, in order to prevent collisions in case of an evasive manoeuvre.
- *Rearward amplification (RA):* The RA is defined as the ratio between the maximum absolute lateral acceleration of the last vehicle and the tractor steer axle. The RA should be as low as possible in order to prevent amplification of vehicle movement, which eventually may result in roll-over of the vehicle.

The three performance indicators were calculated for two vehicle types and different control strategies. A summary of simulation results is given in Table 2. The table shows that basically the performance indicators except off-tracking are significantly worse for the A-double, even when using the control strategies described in the previous sections. Nevertheless, significant improvements are achieved, since the A-double with a non-steered dolly suffers from roll-over without any form of actuation of the dolly wheels.

Table 2 – Simulated performance indicators for assessment of high-speed stability

Simulation case	**Yaw damping [-]**	**Off-tracking [m]**	**RA[-]**
Conventional tractor semi-trailer	0.41	0.36	1.41
A -double, steering	0.20	0.82	1.87
A -double, propulsion	0.16	3.11	2.23
A -double, steering and propulsion	0.18	0.07	1.80

Table 2 shows that a combination of steering and propulsion is the most effective approach, whereas using only propulsion is least effective. This can be partly explained by the fact that limited motor power is available to create the yaw moment required for stabilizing the vehicle. In contrast, steering the tires is a more effective way to create forces in a desired direction. Figure 5 shows the yaw rate response of the last semi-trailer in the A-double configuration with the three different control strategies. The graph shows that the combination of steering and propulsion results in a relatively fast decaying yaw-rate response. The propulsion strategy

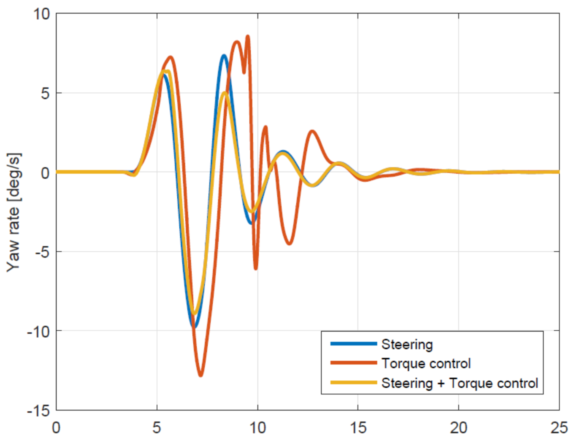

Figure 5 – A-double yaw rate response

results in a very irregular yaw rate response due to loss of road contact, caused by lateral load transfer.

4. Powertrain design

After investigation of possibilities to improve vehicle dynamics using the electric powertrain, potential fuel and cost savings are investigated for the hybrid A-double. The hybrid powertrain consists of a conventional 4x2 tractor and powered dolly, equipped with one or more electric motors and a battery pack. Since two power sources are used, the power split between the internal combustion engine (ICE) and electric motors (EM) must be determined by an Energy Management Strategy (EMS).

4.1 Component selection and sizing

A component selection and sizing study is performed for the electric powertrain in order to determine if the hybrid A-double is feasible in terms of cost, performance and packaging. Since both the sizing of the components as well as the energy management strategy provide degrees of freedom, a nested approach is used to optimize the entire system. The optimal EMS is determined for varying size of the powertrain components.

A model of the (hybrid) powertrain is created in MATLAB to calculate the fuel consumption for the ACEA CO_2 drive-cycle. Since this cycle is ideal, no vehicle is able to exactly follow the prescribed velocity profile. A backward powertrain model is used for optimization of the EMS, which means that the power and torque requirements follow from the input velocity profile and torque distribution. This approach simplifies the optimization process, but requires the input velocity profile to be available and feasible. Therefore, a forward model of the vehicle powertrain is first used to convert the ACEA CO_2 cycle into a velocity profile that can be followed by the vehicle, taking into account the constraints of that specific vehicle (e.g. a tractor semi-trailer combination). The forward and backward models are very similar and both consist of a road load, a generic fuel map of a 330 kW Euro-6 Diesel engine as shown in Figure 6, offline optimized gear-shift strategy, a power consumption map of the EM-inverter combination and a single-resistance battery model. Sizing of the electric powertrain is performed by changing the number of motors, the battery capacity and the gear ratio of the final drive.

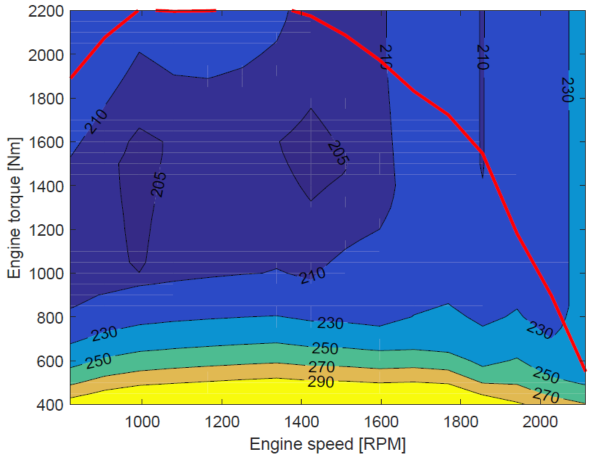

Figure 6- Generic EURO-6 fuel map, showing BSFC in [g/kWh]

4.2 Energy management strategy

The energy management strategy is determined by Dynamic Programming (DP) optimization of the torque split between ICE and EM during the ACEA CO_2 cycle. DP is used, since this method is guaranteed to converge to the global optimal solution if the discretization grid is chosen properly. The battery state of charge (SoC) at the start and end of the cycle are required to be equal in order to enable a fair comparison between different sizes of the battery pack. The

DP solutions, calculated using the backward powertrain model, are tested for validity by using the torque split as input to the forward powertrain model. Since the forward and backward models yielded similar results in terms of velocity profile and fuel consumption, the DP solutions were found to be correct. Figure 7 shows the optimal EM operating points during the cycle for a battery capacity of 45 (blue) and 60 kWh (red) respectively. Furthermore, the motor torque limits are shown in red, and the contour map represents EM-inverter efficiency. It can be seen that the optimal EM torque set point during acceleration resembles a constant-power curve and is independent of battery size. This optimal torque set point can be identified as an assist-only strategy, where the electric powertrain only provides the difference between maximum tractor engine power and power requested by the reference velocity profile. The regenerative braking torque is maximized to the battery or motor limit. If powertrain cost and weight are not taken into account, the ideal battery capacity will be larger than 60 kWh, since a large amount of braking power can be recovered during downhill driving. Although this will be beneficial for fuel savings, it will have a negative effect on powertrain cost. Therefore, the dolly powertrain size is optimized towards total profit instead of fuel consumption.

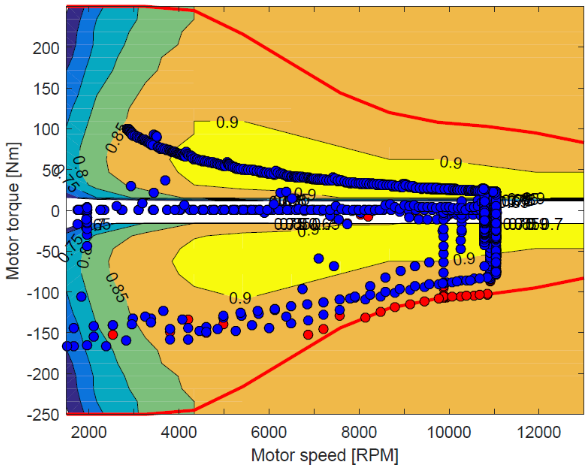

Figure 7 – Optimized motor operating points during CO2 cycle

4.3 Powertrain optimization: costs and fuel saving potential

The cost saving potential of the hybrid A-double is calculated from expected investment and operating costs. The investment costs are defined as the sum of costs for tractor, trailer(s), dolly and dolly powertrain. Dolly powertrain costs are estimated based on price developments of powertrain hardware, normalized to costs per kW and kWh for the drive and battery respectively. Operating costs are defined as the sum of driver and simulated fuel costs, normalized per kilometre. The cost-optimal powertrain is found through maximization of the total profit after driving the ACEA CO_2 cycle for 600.000 kilometres. A weighted combination of load conditions (average loading, maximum loading and varying road inclination) is used for calculation of the profit, which results in a battery size of 35 kWh and total motor output power of 240 kW. For cost calculations, it is assumed that the battery will keep its energy capacity and remains functional until its end of life at 600.000 kilometres.

Next, costs and profit of the optimized hybrid A-double vehicle combination are compared to other conventional vehicle combinations, in order to determine economic viability of a steered and powered dolly. The velocity profile of the conventional tractor semi-trailer combination is used as set point velocity for the forward simulation of fuel consumption for all vehicle combinations. Since this velocity set point is impossible to follow for the A-double due to its increased mass and relatively small powertrain, an Equivalent Consumption Minimization Strategy (ECMS) is used for calculating the torque split during forward simulation instead of DP. Simulations show that ECMS is potentially able to approach the optimal control strategy found by DP. Since the conventional tractor is used in all vehicle combinations, the engine powertrain model (ICE, gearbox and shifting strategy) is identical for all vehicles. The only differences between vehicles are therefore the road load parameters and electric powertrain, including EMS. An overview of the road load parameters used in the different vehicle configurations is given in Table 3. The HCV configuration refers to the combination consisting of tractor, conventional semi-trailer and additional centre-axle trailer, which is already allowed to drive on designated roads in countries like the Netherlands. The vehicle has a maximum GCW of 60 tons and length of 25.25 meters.

Table 3 – Overview of road load parameters for the different vehicle combinations

	Air drag coefficient $[\mathrm{Ns^2/m^2}]$	**Equivalent mass [kg]**	**Auxiliary power [kW]**
Tractor semi-trailer	3.87	32265	7.38
HCV	4.46	45636	8.05
A-double	5.04	58092	8.71

Table 4 gives an overview of the simulated fuel consumption, trip time, and average velocity and CO_2 emissions, normalized per ton km, for the different vehicle combinations. This table shows that the tractor semi-trailer performs best in terms of trip time and average velocity, by sacrificing on fuel efficiency. The A-double hybrid performs best in terms of fuel efficiency when it is allowed to drive more slowly and efficiently. This results in a reduction of 27.8 percent in terms of CO_2 emissions with respect to the tractor semi-trailer combination. However, the additional weight of the electric powertrain is neglected in the calculation for the hybrid vehicle, since the total mass is assumed to be unchanged. As a result, the expected CO_2 reduction will be slightly lower due to the reduced mass of the cargo in the hybrid combination. Table 4 also shows that the A-double hybrid may consume more energy than the non-hybrid, when the electrical powertrain is used to increase velocity and reduce trip time. Calculations show that the optimized hybrid A-double is potentially able to improve profit, while reducing emissions with respect to all other vehicle combinations, depending on the drive-style of the driver.

Table 4 – Overview of cycle performance for different vehicle combinations

Vehicle type	**Velocity set point**	**Fuel [L]**	**Time [s]**	$\bar{V}_x$ **[km/h]**	CO_2 **[g/tkm]**	ΔCO_2 **[%]**
Tractor semi-trailer	Tractor semi-trailer	43.67	4592	78.5	78.13	0
HCV	Tractor semi-trailer	55.90	4742	76.0	66.66	-14.7
A-double	Tractor semi-trailer	67.14	4921	73.3	60.06	-23.1
A-double hybrid	Tractor semi-trailer	67.94	4697	76.8	60.77	-22.2
A-double hybrid	A-double	63.07	4922	73.3	56.42	-27.8

The optimized dolly powertrain and all other dolly components are estimated to cost EUR 25.500 and EUR 40.000 respectively. The total dolly cost will therefore be comparable to that of a tractor. When normalizing the fuel consumption with respect to cargo mass, a fuel saving of 0.085 L/km is found for the hybrid A-double with respect to the tractor semi-trailer combination. Even when the reduction in driver costs are neglected, this fuel consumption will therefore result in a net profit, assuming the service life of the dolly will be similar to that of the tractor. Although the trip time will increase slightly, fuel savings will outweigh the increase in driver costs, also because only one driver is needed instead of two.

5. Conclusions and future work

In this paper, the results of a feasibility study for a hybrid A-double vehicle combination were presented in terms of vehicle dynamics, packaging, CO_2 emissions and costs. The proposed A-double consists of a novel design four-wheel, individually steered and driven dolly, coupled to a conventional 4x2 tractor and two conventional semi-trailers, in order to minimize investment costs and required hardware changes. In terms of low-speed manoeuvrability, the A-double performs similar to a conventional tractor semi-trailer combination, provided that the dolly steering angles of 60 degrees can be achieved. Due to the increased length and higher number of articulation points, the A-double performs worse during high-speed stability tests, although improvements can be made using the proposed propulsion and steering strategies. A nested optimization of the powertrain size and energy management strategy towards maximum profit when driving the ACEA CO_2 cycle, shows that the optimal electric dolly powertrain is affordable and potentially generates profit. Future research should focus on improvement of high-speed stability and packaging, since both are currently limiting factors. In order to gain knowledge on the profitability of the powered dolly concept, more detailed use-cases should be used and durability of expensive components (e.g. battery and drive) should be taken into account.

6. References

- CBS, Transport en mobiliteit 2015, http://download.cbs.nl/pdf/2015-transport-en-mobiliteit-2015.pdf, (in Dutch)
- Duo2 project Sweden, http://duo2.nu/ 2014
- B. Kraaijenhagen, T. Barth, K. Kural, J. Pauwelussen, I. Besselink, A. Prati, M. Meijs, H. Nijmeijer.: Greening and Safety Assurance of Future Modular Road Vehicles, HVTT13 (2014)
- Transformers, http://www.transformers-project.eu, 2017
- EcoChamps, http://www.ecochamps.eu, 2018
- MAZ, https://www.sb.by/files/MT/12/N23/05.pdf, 2012
- Sebastian Franz, Michael Hofmann, Real-Time Control Interface for a Steered and Braked Converter Dolly for High Capacity Transport Vehicles, Master thesis, Chalmers University of Technology, 2015
- R.M.C.M. Wouters, "Preliminary Design of a Smart Powered Dolly for an A-double High Capacity Vehicle", Master Thesis DC2016.081, TU Eindhoven (2016)
- A.G.P. Parfant, "Design and Analysis of a Powered Dolly Concept for an A-double High Capacity Vehicle", Master Thesis DC2017.078, TU Eindhoven (2017)
- Krone, B., Evers, H., "Dolly axle", Fahrzeugwerk Bernard Krone GmbH, Patent, 2009, https://www.google.com/patents/EP1900618B1?cl=fr
- European Commission (2015), "Directive 96/53/EC"
- European Commission (1997), "Directive 97/27/EC"
- Overheid.nl, "Instellingsbesluit Ambtelijke adviescommisie LZV (2015), http://wetten.overheid.nl/BWBR0016098/geldigheidsdatum 11-01-2016
- Kural, K., Prati, A., Besselink, I., Pauwelussen, J. et al. (2013), "Validation of Longer and Heavier Vehicle Combination Simulation Models, SAE Int. J. Commer. Veh. 6(2):2013, doi:10.4271/2013-01-2369.