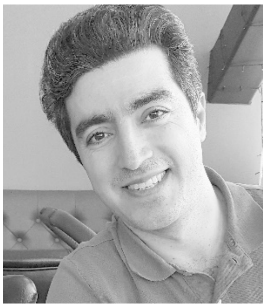
BENEFIT ANALYSIS OF INTRODUCING ELECTRIC PROPULSION ON CONVERTER DOLLIES

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Abstract

Long combination vehicles (LCVs) demonstrated substantially lower cost and energy consumption compared to tractor-semitrailers. However, they suffer from reduced longitudinal performance. Distributed propulsion over axles, i.e., electrically propelling trailers or the converter dolly (e-dolly), can resolve the reduced longitudinal performance and improve energy efficiency of these vehicles. This paper implements an advanced predictive controller for distribution of propulsion, regenerative and service brakes between axles, which ensures both optimal energy efficiency and safety. To generate the results, 4000 different roads with different topography profiles were generated statistically and used for testing the controller performance. The simulation results indicate that the fuel saving of the hybrid A-double, i.e., the one with e-dolly compared to the conventional A-double is, on average, 12%, 14.5%, 16.5%, and 17.5% on flat, predominantly flat, hilly, and very hilly roads, respectively. Both vehicles were equipped with the advanced controller. In addition, with that fuel saving, the hybrid A-double showed lower total cost of ownership in all roads if the distance traveled per year is higher than 45000 km. Moreover, the longitudinal performance, i.e., startability, gradeability, and acceleration capability were improved by 27%, 25%, and 8%, respectively.

Keywords: Electric Dolly, Electric Trailer, Predictive Energy Management, Long Combination Vehicles, Total Cost of Ownership, Lateral Stability, Performance Based Standards, Hybrid Vehicles

1. Introduction

CO_2 emissions of new heavy vehicles must be reduced by 30% before the year 2030, compared to the emissions produced in 2019, according to Regulation (EU) 2018/842, and 45% reduction of CO_2 emissions according to the new proposal by EU commission. Deploying longer and heavier vehicles - also known as LCVs and high-capacity vehicles - on roads can help to meet the growing demand for road freight transportation, as well as contribute to a lower share of CO_2 emissions. For example, on average, conventional LCVs of four vehicle units with a diesel engine could reduce total cost of ownership (TCO) and fuel consumption by approximately 30% and 17%, respectively, compared to tractor-semitrailers as suggested by Ghandriz et al. (2020).

However, conventional LCVs suffer from reduced longitudinal performance, Kharrazi et al. (2014-2017), e.g., startability, gradeability, and acceleration capability due to limits on the driven axle(s)' propulsion torque and vertical load of the first towing unit. This problem can be solved by distributing propulsion over the axles of other vehicle units. Electric propulsion can be introduced on trailers or converter dollies, each exhibiting its pros and cons. Introducing electric propulsion on trailers and semi-trailers is easier w.r.t. to packing and space of the electric drive train compared to dolly converters. This implies fitting of larger batteries, that can contribute to a longer electric range of the LCV. However, unless the electric trailers are dedicated to being always connected to the towing unit(s), they have different utilization levels, e.g., by being standing still on hubs for performing loading-unloading operations, which increases the overall TCO of the transport operator, Ghandriz et al. (2021). Electric converter dollies, however, are supposed to have the same utilization level as the first towing unit of LCVs. Therefore, this report focuses on electrifying converter dollies rather than trailers. Most of the derived methods and conclusions, however, are also applicable to dedicated trailers.

The benefits of introducing electric propulsion on converter dollies can be summarized as follows:

- Improved longitudinal performance: startability, gradeability, acceleration capability, and down-hill holding capability, as well as increased range of LCVs.
- Reduced fuel consumption of LCVs where the first towing unit is a conventional diesel tractor.
- Reduced TCO where the first towing unit is a conventional diesel tractor and for utilization level higher than a certain threshold.
- With steerable electric dolly and automated coupling comes the possibility to automize shunting at loading/unloading and hence increase transport efficiency.

Steerable dollies, however, are out of the scope of this report.

Distributed propulsion over axles of all units, and in this case, converter dollies, increases the degrees of freedom of an LCV's propulsion system. The challenge is to optimally distribute the total torque between all driven axles to ensure energy efficiency and lateral stability. Such a vehicle is a hybrid vehicle due to the two different sources of energy: the first unit is propelled using diesel fuel and the e-dolly is propelled using electric energy. Optimal control, in particular model predictive control (MPC), is a suitable approach for minimizing hybrid vehicle energy consumption based on information about road topography and the surrounding environment according to Ghandriz et al. (2020- 2021), Murgovski et al. (2016), and Johannesson et al.

(2015). In addition, in LCVs the lateral stability constraints can be added to the MPC by modeling the vehicle combined nonlinear longitudinal and lateral motion and adding constraints on lateral acceleration and tires' nonlinear forces according to Ghandriz, T., (2020). In such a problem the states are the speed of the LCV, battery state of charge, time, lateral velocity, yaw angle of the first vehicle unit, and articulation angles and their derivatives. The resulting problem is a novel advanced controller for combined predictive energy management (PEM) and motion optimal control of LCVs, in form of a nonlinear optimal control problem (NOCP).

This paper summarizes the formulation of combined PEM and motion optimal control of LCV according to Ghandriz, T., (2020), and shows the fuel-saving offered by this controller on different road types in terms of topography. On very hilly roads, for example, for the given LCV and e-dolly specification, simulations show up to 22% savings in fuel compared to a conventional LCV. Both vehicles follow their own optimal speed profile with a same arrival time. This is when the pushing and pulling of the front and rear vehicle units are allowed by the e-dolly under dynamic lateral stability constraints. If unnecessary conservative constraints are used where the e-dolly propels not more than the first unit and brakes not more than the other axles, the fuel saving is reduced by 13 percentage points, i.e., the saving would be 9% instead of 22%, for the given road and vehicle.

The real-world experiment of the controller is ongoing. The preliminary test results confirm the above figures with a 10% error compared to the simulation. In all the cases the controller follows charge sustaining strategy meaning that the battery state of charge at the beginning and the end of the trip has the same value. Important vehicle parameters are given in Table 2 . Figure 1 shows the e-dolly that is used for testing the controller.

The fuel saving offered by the controller is limited to hybrid LCVs. If the first tractor would be electric there would be still energy savings resulting from speed optimization but not as much as a hybrid counterpart, however, in that case, a safe driving can still be ensured using the suggested controller.

Figure 1 – E-dolly prototype used for testing the controller

2. Productivity and Total Cost of Ownership

In this paper, the yearly total cost of ownership (TCO) per unit freight transported and per kilometer is used as a measure for evaluating the productivity of the vehicle. This is especially important when the vehicles' uptime is different due to different powertrain, payload, waiting times, loading-unloading, etc. TCO is a measure for comparative analysis of different transport solutions from consumers' perspective (Ghandriz et al. 2020-2021) and when mentioned per unit freight transported and kilometer traveled, the effects of product price, operational costs, different payloads, uptime, and utilization are also considered in the productivity measure.

Following the definition given in Ghandriz et al. (2020), the annual TCO per unit freight transported and per distance traveled includes the operational costs and the depreciation of the purchase price. Operational costs comprise annual costs of electricity, diesel fuel, driver, vehicle maintenance, taxes, and insurance. The purchase price included the price of the vehicle components and loading-unloading (LU) components. There was no charging infrastructure included because the e-dolly is assumed to not charge from an external grid.

The annual number of freight units transported is a function of utilization level, maximum possible number of trips per year, and payload. Utilization level is defined as the fraction of yearly time (365 days) when the vehicle is in operation. Trip time is sum of the driving time, loading-unloading time, charging time (if any), waiting or queue time at depots, and the driver rest time if it is more than the other waiting times. In this paper, the higher limit for economic lifetime is eight years. The economic lifetime of the vehicle also ends if it travels more than one million kilometers. In addition, battery-degradation model was implemented according to Ghandriz et al., 2020. The maintenance cost of e-dolly was considered as 50% of that of a conventional diesel vehicle, as suggested by Feng and Figliozzi, 2013, and Lee et al., 2013 for electric vehicles. Moreover, the resale value of batteries including the replaced ones might be different from the rest of the vehicle considering the battery state of health. In this paper, the batteries need to be replaced ifthe battery capacity reached 80% of the initial capacity with no resale value. Any possible second life application was neglected. Furthermore, a conservative additional payload of 2% was assumed for e-dolly, without considering any incentives. The exact bonus payload depends on national regulations where these LCVs are allowed.

TCO is used as a comparative measure to reflect the differences between an A-double combination vehicle with e-dolly converter and its conventional counterpart. Therefore, to some extent, errors in evaluation of the cost factors that are the same for these two vehicles do not harm our comparative analysis. However, the cost factors and parameters that are different between these two vehicles need to be accurately evaluated. They include price of e-dolly compared to conventional dolly, its weight and change of the payload, and the energy or fuel consumption. The later requires accurate models and controller, i.e., PEM and motion control which follows next.

3. Predictive Vehicle Energy Management and Motion Control

There are different approaches and types of controllers for vehicle energy management found in the literature, e.g., Ghandriz T., 2020, Ghandriz et al., 2021, Murgovski et al., 2016, and Johannesson et al., 2015. For hybrid vehicle and distributed propulsion, a controller that demonstrates the highest fuel saving and at the same time guarantees a safe motion is a model prediction controller according to (Ghandriz T., 2020). Such a controller needs information of the surrounding environment such as the upcoming road topography and curvature, to be able to distribute propulsion between axles optimally in terms of energy and safety for the whole trip. A simple example of saving fuel when the information about the upcoming road is available is to use the electric energy now if there is a downhill ahead to leave room for battery to be charged later. A simple example of safe motion is to reduce speed now, with an optimal brake distribution, before the vehicle reaches a sharp curve on the road. A more advanced example is, because of combined slip behavior of tires, the maximum lateral and longitudinal force of tires are coupled. Therefore, longitudinal force reduces the maximum lateral force that the tire can tolerate. On curved part of the road, reduced maximum lateral force can cause large side slip and swinging (see Figure 6). The controller predicts such a situation and distributes the longitudinal forces between axle for the whole prediction horizon such that the tires' lateral force needed for negotiation of the upcoming curve stay away from the dynamic higher limit. At the same time, controller minimizes the energy consumption over the horizon within the lateral safety limits.

4. Subject Vehicles and Use-cases

Subject vehicle for tests and simulations are A-double combination vehicles with and without e-dolly. A schematic of the vehicle is shown in Figure 2 The gross combination weight (GCW) of the vehicle is assumed to be 80 ton. The net combination weight of the two vehicles are 33.65 ton and 35.7 ton. Therefore, the additional weight of e-dolly compared to a conventional dolly is 2.05 ton. The payload of the conventional A-double is 46.35 ton, and if it is allowed to consider 800 kg additional payload for A-double with e-dolly, according to EU directive 2015/719, makes its payload 45.1 ton. In addition, the volume capacity of both vehicles is 134 m^3. Some of vehicle parameters are shown in Table **2** .

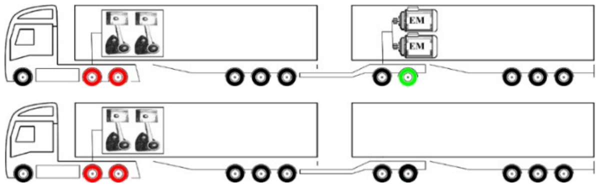

Figure 2 – (top) The A-double with e-dolly tested for the predictive lateral stability control and energy management NOCP, and used for comparative analysis against a conventional counterpart (bottom)

Table 2 – Some of the important vehicle parameters

Parameter	**Value**	**Parameter**	**Value**
GCW of both vehicles	80 ton	Vol. capacity (both vehicles)	134 m3
Payload, A-double with e-dolly	45.1 ton	Payload, conv. A-double	46.35 ton
e-dolly batteries energy capacity	18 kWh	Recommended e-dolly batteries usable SOC window	20%-60%
e-dolly additional weight compared to conventional dolly	2.05 ton	Bonus payload because of electrification	800 kg
Prices: conv. A-double, loading-unloading (4 additional semitrailers)	247 k€, 164 k€	Prices: e-dolly (additional to conv. dolly),	45 k€

Tractor ICE max power	550 kW	e-dolly max powers: batteries, EMs	150 kW, 2x160 kW
Tractor ICE max torque	3500 N.m	e-dolly EMs max torque	2x480 N.m

The results were generated considering different road topographies with 200 km length. The vehicle continues delivering goods with full load capacity on that road during its lifetime. Examples of road topographies and speed limits are shown in Figure 4.

5. Results

5.1. NOCP Solution and Fuel Saving

The initial real-world test of the NOCP of PEM on an especial proving ground showed a substantial fuel saving close to the simulation results. The real-world test is ongoing, and more tests are needed before publishing the detailed results. However, the fuel saving as the result of implementation of the NOCP of PEM varies depending on the road topography and traffic. The conventional dolly is also equipped with PEM (or a predictive cruise control) which produces an optimal speed profile. It is reasonable to assume that both vehicles benefit from such an advance controller to have a fair comparison. Different road topographies comprise four categories: flat, predominantly flat, hilly, and very hilly according to Ghandriz et al., 2020, and Romano et al, 2022. In each category 1000 road profiles of length 200 km were created and the NOCP of PEM was solved for. The results of fuel saving are shown in Figure 3 and Table 3 using estimated probability density.

The A-double with conventional dolly equipped with PEM, i.e., with optimal speed profile, demonstrates a fuel saving of 17%, 15%, 12%, and 8% on very hilly, hilly, predominantly, flat, and flat roads, respectively, compared with a vehicle that tries to keep the road speed limit and the same arrival time. The fuel saving of an A-double with e-dolly shown in figures Figure 3 and Table 3 are in addition to these fuel savings. Figure 4 illustrates the road topography profiles, velocity limits (legal limit and traffic), and the controller results related to the use-case that gives the average fuel saving.

The shown NOCP does not put any constraint on the torque of e-dolly to limit the trailer coupling reaction forces. Therefore, there might be situations that e-dolly pulls or pushes the vehicle units in front of it. In general, such situation may cause instability because of nonlinear vehicle properties, combined slip tire behavior, uneven distribution of axle loads, road curvature, high speed, etc. However, the constraints on lateral stability included in the proposed NOCP avoid any instability, e.g., swing and jack-knife, by monitoring the vehicle motion over the prediction horizon and optimally distributing the propulsion and brakes between axles. In that case, average fuel savings as the result of implementing the NOCP of PEM are 17.5%, 16.5%, 14.5%, and 12% on very hilly, hilly, predominately flat, flat roads, respectively, compared to a conventional vehicle driving with an optimal speed profile. If, for any reason, e.g., legislation, pushing or pulling of other vehicle units by e-dolly is not permitted, on average, the fuel saving would be 4.5%, 4%, 3%, and 2.5% on very hilly, hilly, predominately flat, and

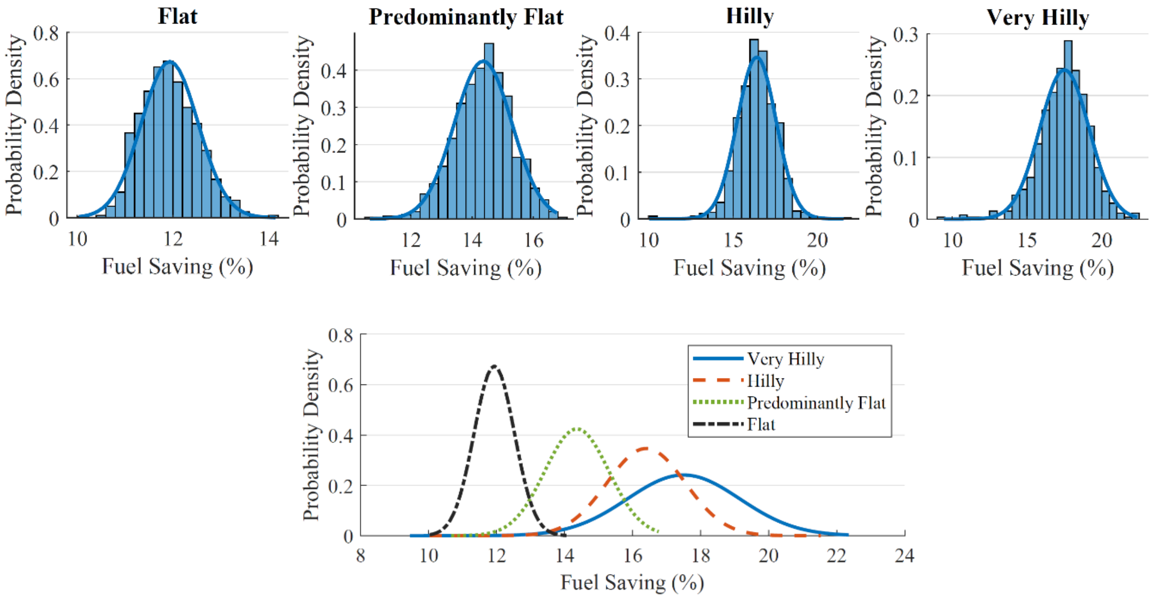

Figure 3 – Fuel saving of an A-double with e-dolly obtained by solving NOCP of PEM compared with a conventional A-double with an optimal speed profile.

Table 3 – Average fuel saving of different control strategies obtained by solving NOCP of PEM compared with a conventional A-double with an optimal speed profile

Control strategy	Flat	Predominantly Flat	Hilly	Very Hilly
PEM with lateral dynamic constraints allowing push and pull	12%	14.5%	16.5%	17.5%
PEM with no push or pull by e-dolly	2.5%	3%	4%	4.5%

flat roads, respectively. Figure 5 illustrates the optimal speed, state of charge (SOC), gear, and the propulsion and brake forces generated by NOCP before and after limiting the coupling forces, i.e., when e-dolly did not propel more that the tractor and did not brake more than the other axles, on a hilly road.

5.2. NOCP Solution and Improved Safety

As it was already mentioned, there might be situations when using the e-dolly for regenerative braking and propulsion may cause instability of the vehicle. However, the proposed NOCP predicts possible unsafe situations and avoids them by adjusting the vehicle speed before reaching the unsafe situation and by distributing the propulsion and braking optimally in terms of energy usage. An example of controller performance in such a situation is shown in Figure 6 and Figure 7 . Figure 6 illustrates a jackknife situation caused by implementing a poor controller which allows regenerative braking on the driven axle of the e-dolly and neglects

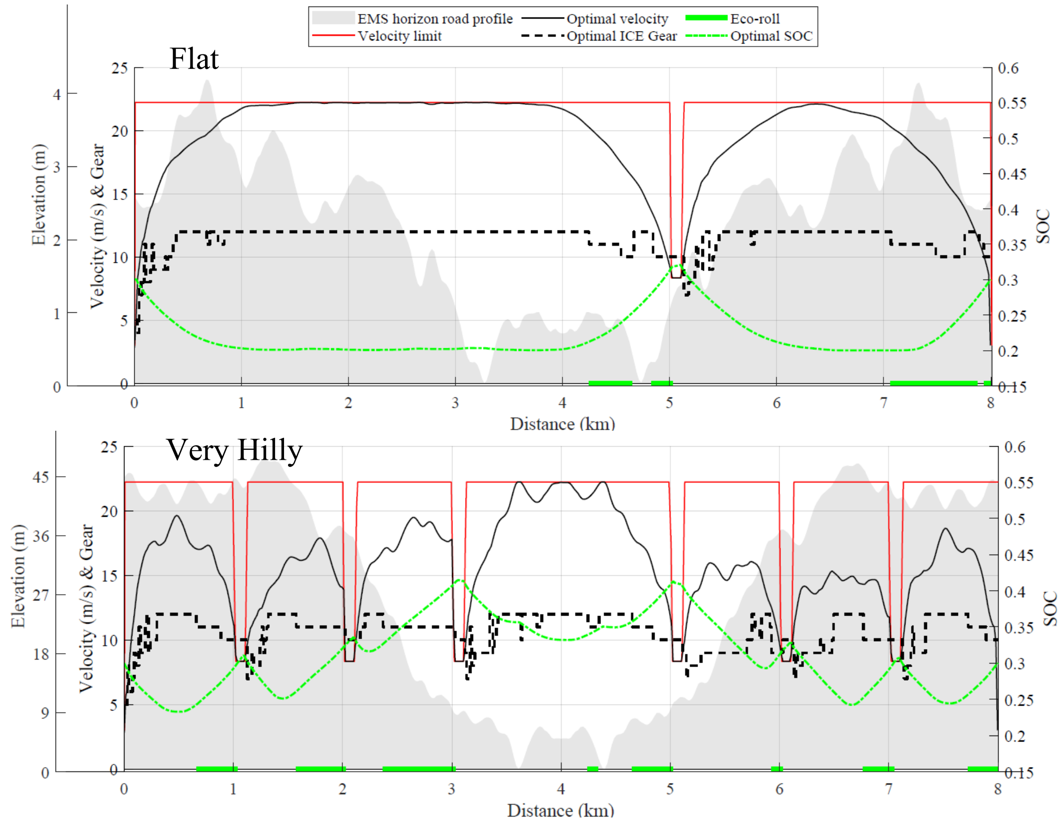

Figure 4 – Road topography profiles, velocity limits, optimal velocity, optimal state of charge (SOC), and optimal gear trajectories of a section of the road for each of the road hilliness categories related to the average fuel saving. Eco-roll means when ICE is off.

combined slip effect of the tires. Figure 7 illustrates the performance of the advanced controller which avoids jackknifing by including the predictive lateral stability constraints. The forces of the e-dolly-driven axle are shown before and after the inclusion of the lateral stability constraints at the bottom of the figure.

5.3. Longitudinal Performance Measures

In addition, this paper provides values for the improvement of the longitudinal performance of a test-case LCV using the openPBS tool, Jacobson et al., 2022, or similar. Measures that are used for evaluating the longitudinal performance of the two vehicles are startability, gradeability, and acceleration capability according to Kharrazi et al., 2014, 2017. Table 4 provides the values of those measures for the two different vehicles.

Table 4 – Longitudinal Performance Measures

Performace measure	Conventional A-double	A-double with e-dolly	Improved percentage
Startability (%)	13.7	17.4	27%
Gradeability (%)	2.85	3.55	24.5%
Acceleration capability [s]	12.9	11.85	8%

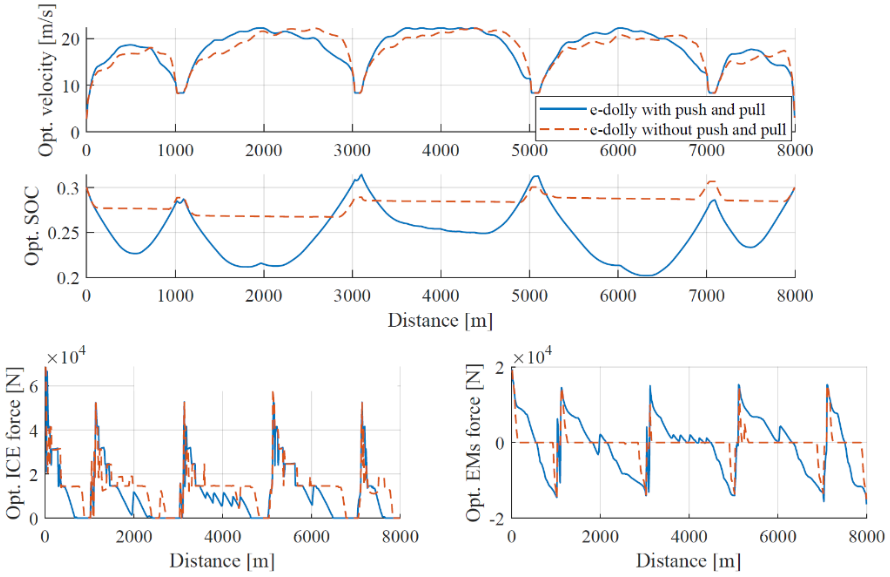

Figure 5 – Solution of PEM NOCP, optimal velocity, SOC, and gear, together with optimal force trajectories, on a hilly road, when (1) pushing and pulling of other vehicle units are allowed by the e-dolly, and (2) when they are not allowed, i.e., e-dolly is not allowed to propel more than the tractor and to brake more than the other axles.

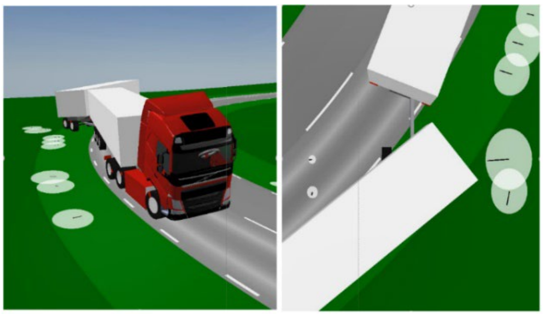

Figure 6 – A jackknife situation caused by implementing a poor controller

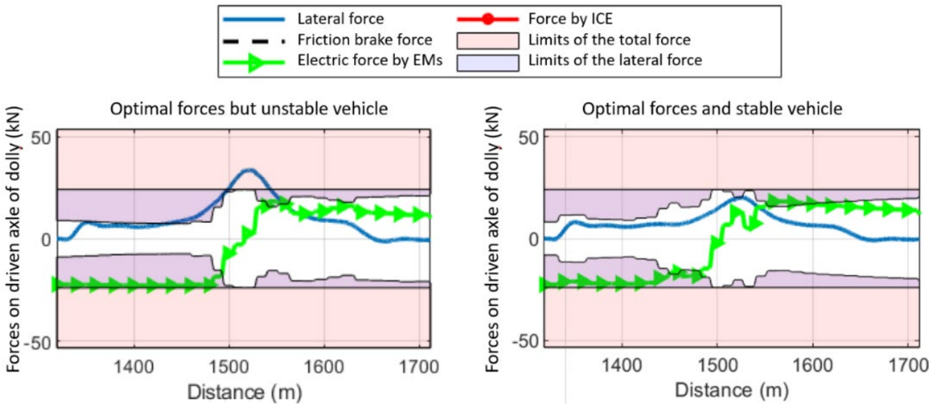

Figure 7 – the controlled LCV (A-double) and the controller performance

5.4. TCO

An e-dolly is more expensive and heavier than a conventional dolly, therefore it causes a higher investment price and lower payload of the vehicle combination. However, it offers fuel saving and lower CO_2 emission, and thus lower operational cost. TCO per unit freight transported and per unit distance traveled includes all these trade-offs from consumers' perspective. Figures 8-10 can be used to understand those missions where an A-double with e-dolly is a more economically viable choice that conventional A-double. The utilization level (as well as kilometer traveled per year) is varied. There is a certain utilization breakpoint that an A-double vehicle with e-dolly becomes cheaper than a conventional A-double. That breakpoint position is different for different road topographies. The average annual TCOs per ton and per kilometer as functions of utilization for different road topographies are shown in Figure 8 . Here, utilization means the fraction of yearly time when the vehicle is on operation, i.e., it is either on road, or standing still because of queue, driver resting, and/or loading-unloading. In this paper, 10% and 40% utilization correspond to about 35000 and 150000 km/year, respectively.

Furthermore, if the volume of the transported freight is more important than their weight, i.e., if the freight is light then the payload loses its significant and the transport income is calculated based on transported volume. In that case, TCO per unit volume is relevant as shown in Figure 9, where vehicle with e-dolly shows even lower TCO compared to the conventional counterpart. The cost factors of TCO of the two vehicles on a flat and very hilly road are shown in Figure 10.

Finally, Figure 12 shows the annual TCO per unit freight transported and per distance traveled on a very hilly road (as the best road for e-dolly) where the pushing and pulling by e-dolly is not allowed. The vehicle with e-dolly, in that case, has a higher TCO compared to the conventional vehicle.

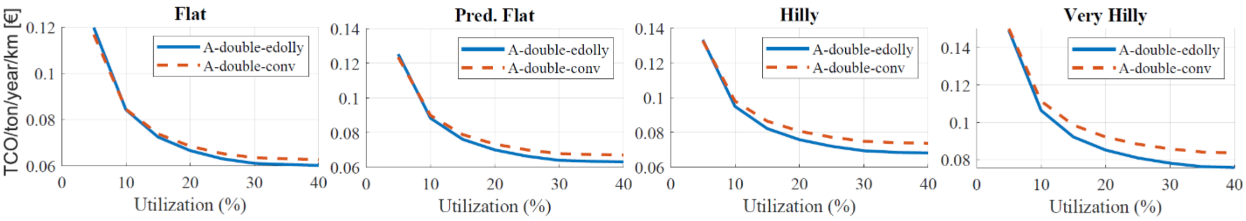

Figure 8 - The average annual TCOs per ton kilometer as functions of utilization

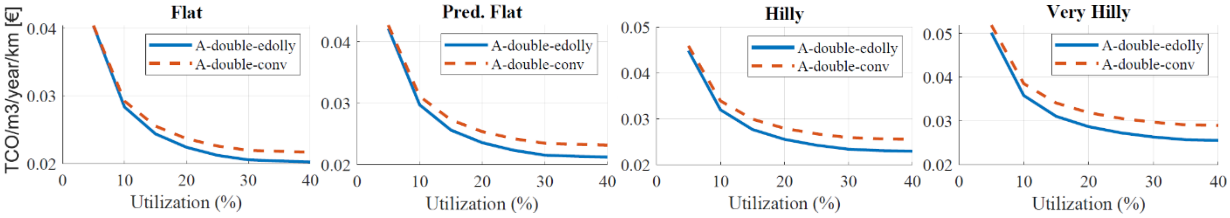

Figure 9 – The average annual TCOs per unit volume (m3) and per kilometer as functions of utilization for different road topographies

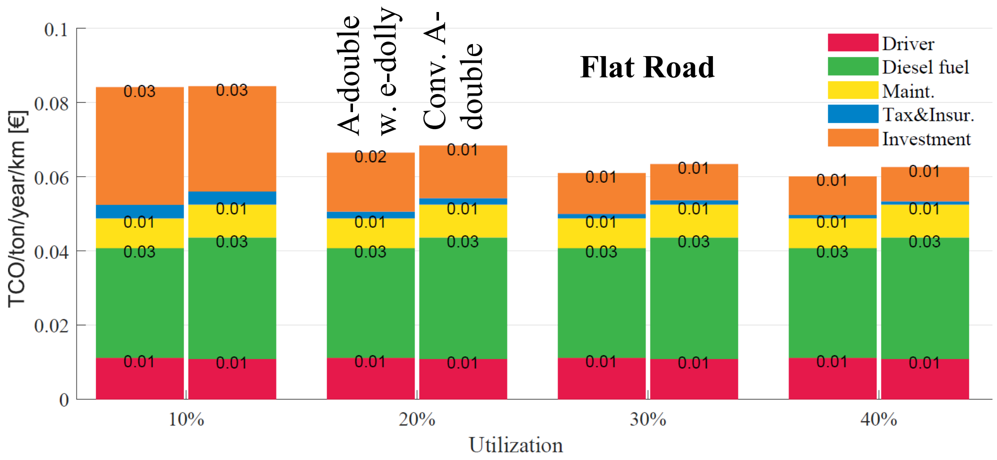

Figure 10 – Cost factors of TCO. In each group of two columns, the left column relates to vehicle with e-dolly and the right column relates to the conventional vehicle

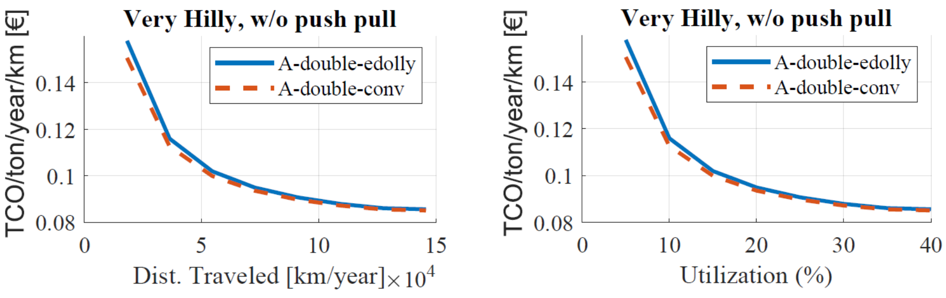

Figure 12 – Annual TCO per ton kilometer on a very hilly road where the pushing and pulling by e-dolly is not allowed

6. Discussion and Conclusion

The calculations and presented results are valid for the given vehicle and e-dolly parameters. Variation in vehicle parameters affects the fuel saving and TCO. In addition, lower vehicle weight may increase fuel saving caused by e-dolly because limits of e-dolly torque and power are less reached. Moreover, high variation in speed because of legal limit, traffic, or curvature, increases the fuel saving offered by e-dolly. Furthermore, in all studied roads, performance of the e-dolly was limited by the battery power rather than the SOC. Therefore, SOC window of 40% could be enough which also increased the battery life of our non-plug-in e-dolly.

The improved longitudinal performance can be a reason for e-dolly be used when the first towing unit is an electric tractor. Detailed TCO analysis of fully electric combination with distributed propulsion is left for future studies.

The conclusion and results can be fairly generalized for dedicated e-trailers with similar utilization as the rest of the vehicle.
Comparisons with non-predictive ad hoc controllers is left for future studies. There are many details of controller implementation, performance, and the solution method that are omitted in this report. The interested reader is referred to the reference publications.

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