Assessment of Innovation Concepts for Truck-Semitrailer Combinations within the TRANSFORMERS Project

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1. Introduction

Today trucks are designed and optimized towards a limited variance set of usage and for maximum payload. Future trucks-trailers are easily adaptable for each freight, load and mission. And, in the operation phase, the vehicle combination automatically adjusts itself to the actual driving environment (i.e. traffic situation, topology, and payload). This option has large potential to contribute to the achievement of the EC's targets for reducing the consumption of fossil energy resources, increasing transport - and fuel efficiency. The objective of the TRANSFORMERS project is to develop and demonstrate innovative and energy efficient trucks and load carriers for long distance transport assignments with an improved load efficiency leading to an overall 25% less energy consumption on a ton.km basis and a lower impact on the road infrastructure.

This overall goal will be achieved by the following key innovations:

- A distributed, modular, and mission adaptable Hybrid-on-Demand (HoD) driveline
- Mission-based configurable aerodynamic overall truck-trailer design
- Loading efficiency optimized trailer interior design

The TRANSFORMERS project focused on achieving these key innovations within the existing European legal and regulatory framework, but has also suggested changes where necessary to introduce new technologies easier.

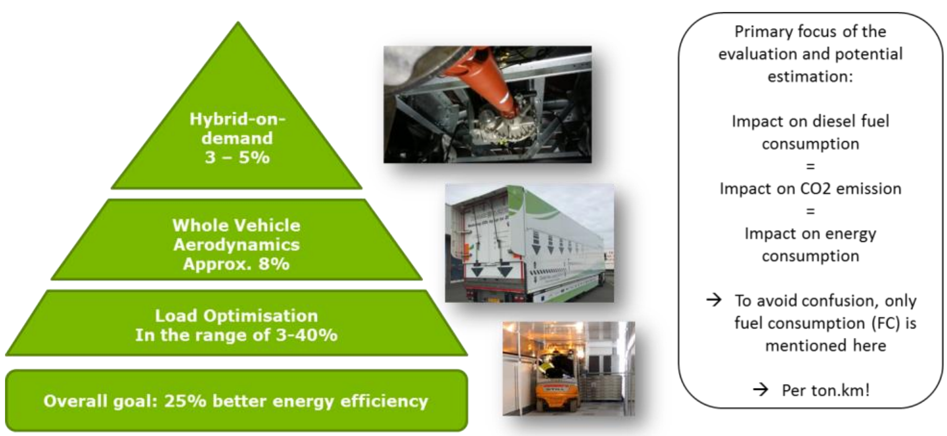

Figure 1 TRANSFORMERS Project Goals [1]

The TRANSFORMERS project consortium consisted of 13 partners from the truck, trailer and road transport industry as well as scientific partners. The project was co-funded by the European Commission in the FP7 programme. The project ran from September 2013 until August 2017. This paper presents the methodology and assessment results illustrating fuel savings of 25%, and higher.

Keywords: CO2-Reduction, Hybridisation, Energy Efficiency, Environmental Impact

2. Truck-Trailer Innovations

Innovations within whole-vehicle approaches present an interesting opportunity for CO2 reduction for freight transport [2][3]. Two demonstrator trailers were designed and developed by VEG and SCB in close cooperation with partners for use in combination with modified tractors by DAF and VOLVO. Both trailers differ in terms of their key technologies:

- The **load optimization trailer** focusses on the increased efficiencies gained by additional loading capacity and advanced aerodynamics;
- The **energy efficiency trailer** focusses on the increased efficiencies gained through advanced aerodynamics and energy recuperation.

Load Optimization Trailer

The load optimization trailer comprises aerodynamic features and innovations to carry additional goods.

- The aerodynamic features comprise *Side Wings, Boat Tail and a 4-segment Movable Roof and a Front Bulkhead*. The movable roof is made out of a foam sandwich panel with aluminum side plates that cover the side walls. It can go stepless to all positions that can be preprogrammed. The movements are made with the same spindle system that moves front bulk head and back portal. The power comes from battery system that must be charged by the truck while driving. The aerodynamic benefits of the sectional roof will not be tested, but calculated. The front bulkhead has been built with flexible corners to gain extra inner length. The front bulkhead is made of two parts sliding in each other. The height setting of the front bulkhead is automated and done by electromotor and spindle. The movement is controlled by programmable logic controller In the front Bulkhead the interfaces for the flexible floor are also integrated.
- The *Flex Floor* is made out of a galvanized steel frame with aluminum plates. It locks itself in every position with a clicking mechanism so it never can drop down. It is pushed against end stops, who's position can be preset, with a fork lift with long arms. The arms of the forklift fit in two lever that pop up out of the floor by hand. When the Flex Floor is not used it is hidden in the floor.

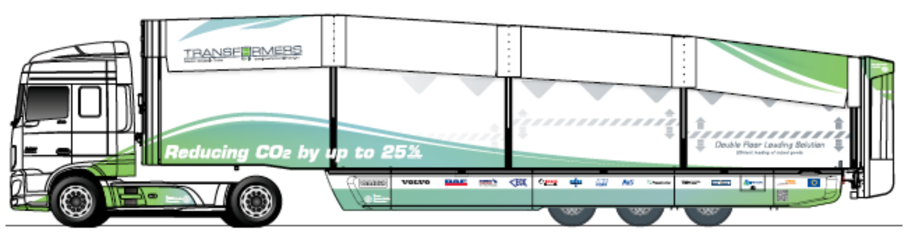

Figure 2: Load optimization trailer

Energy Efficiency Trailer

The energy efficiency trailer comprises aerodynamic features and a Hybrid-on-Demand system (see Figure 3 below).

- Similar to the Load Optimization Trailer, a new body for a standard curtainsider was developed within the project to include an aerodynamic *bulkhead, side wings and a boat tail*. The one segment roof can be lowered 500 mm at the front and 800mm at the rear. The lifting system consists of a hydropneumatic pump and hydraulic cylinders which are placed on all 4 edges of the trailer. Maximum overall height of the trailer is 4000 mm (which is standard for most of the semitrailers used in the EU) and the minimum height is 3500 mm at the front and 3200 mm at the rear. With this stroke it is possible to adjust the trailer to the cabin height of the truck, as long as the cargo height allows it. It is also possible to set the roof into a position with an inclination angle to the rear, e.g. 4000 mm overall height at the front and 3200 mm at the rear to reach a higher aerodynamic efficiency.

- The hybrid-on-demand (HoD) driveline consists of an electric motor and generator (EMG), a gearbox with in integrated clutch, a cardan shaft and a drive axle which is integrated in the SCB air spring system. As energy storage a lithium-ion battery is used. In the TRANSFORMERS project these parts were integrated in an already existing trailer chassis. All necessary adaptions to the chassis and the design of new parts to be able to integrate the EMG and the gearbox and to install the drive axle into the existing air spring suspension have been designed and constructed within the scope of the project.

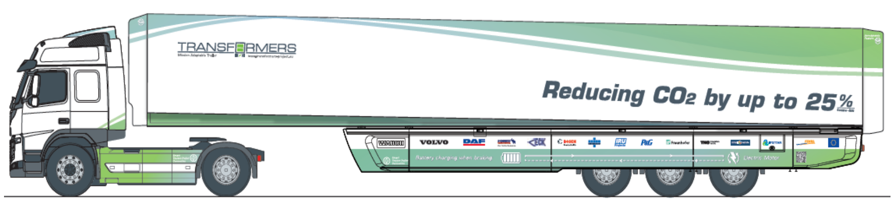

Figure 3: Energy efficiency trailer

3. Evaluation and Assessment Methodology

In order to assess the project goals of achieving a 25% reduction per ton.km, an evaluation framework has been defined in which the process of the evaluation is specified. Traditionally, the best way to evaluate the effectiveness of a technology or innovation is by testing it under real-life driving. The downside of measurement campaigns is, however, that they are resource-demanding and often focus on a narrow field of application. Due to variations in traffic, ambient conditions and driver behaviour, they are less reproducible. High-fidelity simulations are highly reproducible and well suited to determine the effectiveness under a wide range of conditions. However even then, high fidelity simulations are time consuming and complex in their setup and execution.

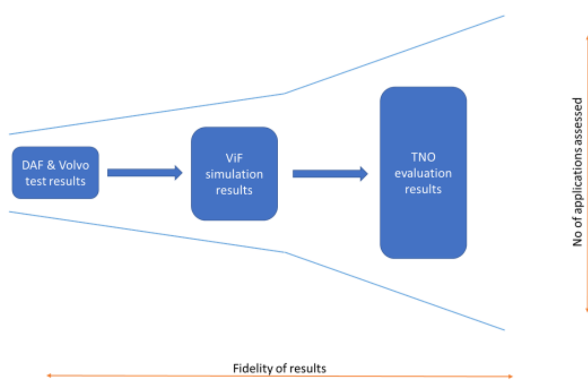

Figure 4: Assessment Steps – Scope Widening and Modelling Fidelity

The evaluation framework described in this paper makes use of the results obtained from measurements and simulation and expands these to a wider range of applications, i.e. different payloads, combinations of configurations. For this purpose, the results obtained at an earlier stage are fitted to a simplified vehicle model.

The evaluation is made in terms of:

- The impact on driving dynamics,
- The impact on loading efficiency (payload capacity and handling improvements), and
- The impact on energy efficiency, CO_2 emissions and fuel consumption (including both the effects of the HoD system and/or the aerodynamic measures)

Furthermore, the business case for these innovations is evaluated for a number of selected use. In addition to the evaluation of the current configuration, the final report will also present recommendations for further improvement of the TRANSFORMERS innovations, an outlook for the market potential of the TRANSFORMERS innovations, potential implementation strategies, and next steps as seen from the perspective of end users and OEM.

High Fidelity Modelling Environment

In Figure 5 the AVL Model.CONNECT model for the HoD Truck/Trailer combination can be seen. On the far left side is a block that contains all the parameter that will be changed during different simulations. That is followed by the 'Environment' model and the truck components. The block with the truck symbol in the middle is the 'Driving Dynamics' model which is a link between the truck components and the trailer side. On the right side the HoD components (EMG, ESU, Thermal model and Management System) are placed. The thick violet lines are bundled signals and the thin ones are single signals.

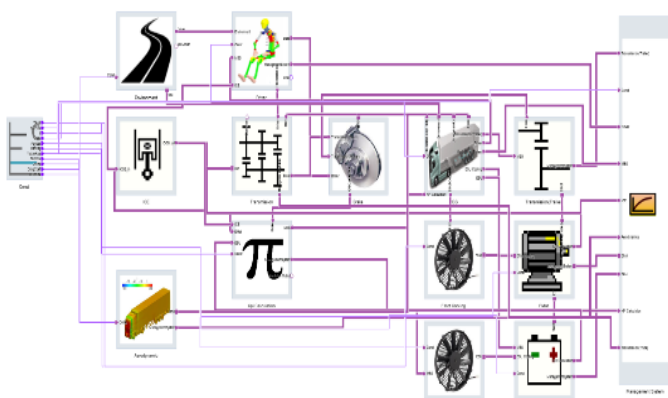

Figure 5: AVL Model.CONNECT Model

Demonstrator Testing Methodology

In the project two innovative semitrailers were developed and tested. The Hybrid-on-Demand driveline in the Energy Efficiency Trailer that was built by Schmitz Cargobull.

Due to the applicability of the new system over multiple truck brands was an important objective as well, this trailer was combined with two conventionally propelled trucks (one from Volvo and one from DAF). Figure 6 shows one combination during public road testing. The mechanical integration of the HoD driveline is described in Meurer et. al. [3], based on end user requirements [4]. Details about the electrical and electronic architecture of the driveline, the safety concept and the commissioning of the driveline are described in Nitzsche et.al. [5].

Public road testing was performed by Volvo according to an in-house procedure that is similar but not identical to the SAE J1321 procedure. Two vehicle combinations [5], one following the other, are driven at the same time on the same route with a minimum distance of 300 m between them while retaining almost exactly the same speed. One of the vehicles was the TRANSFORMERS combination, the other was a so-called normalization vehicle, which is used to eliminate effects caused by changing conditions between the test runs, like weather conditions. To ensure a consistent evaluation, the tests were repeated a number of times. The outcome of each test is the difference in fuel consumption between the TRANSFORMERS trailer with the HoD system on and off. The cycles were driven in respect with the laws applicable in Sweden, and the maximum speed on the motorway set to 80 km/h. When the cruise control was engaged, +/-5 km/h over-speed/under-speed was however allowed on the vehicle.

Figure 6: TRANSFORMERS Truck-Semitrailer combination during public road testing

In the calculations both types of energy (fuel energy + electric energy supplied by the battery) are treated equally. However, their respective drivelines have different efficiencies. The total energy supplied for propulsion is smaller with the HoD active than without. Table 1 illustrates sample results from four repeat test routes ‘BOGA’, combined with both motorway and non-motorway driving (presented here in five sections). BOGA is a 129 km long cycle and is composed of country road and highway (motorway) parts.

Table 1.: Example Results from BOGA Test[1]

		Full cycle			Hällered ==> Borås			Borås ==> Landvetter			Landvetter ==> Partille			Partille ==> Alingsås			Alingsås ==> Hällered		
Test name	Initial SoC	Fuel only	SoC Diff	Fuel + SoC compensation	Fuel only	SoC Diff	Fuel + SoC compensation	Fuel only	SoC Diff	Fuel + SoC compensation	Fuel only	SoC Diff	Fuel + SoC compensation	Fuel only	SoC Diff	Fuel + SoC compensation	Fuel only	SoC Diff	Fuel + SoC compensation
Ref. BOGA	-	37.1 L/100km			48.7 L/100km			26.7 L/100km			41.6 L/100km			39.4 L/100km			48.2 L/100km		
BOGA 1	42%	-5.1%	-4%	-4.7%	3.3%	7%	-1.8%	-8.0%	-10%	-3.5%	-6.9%	7%	-16.0%	-3.3%	-10%	0.9%	-10.5%	2%	-11.3%
BOGA 2	41%	-3.2%	-1%	-3.1%	1.4%	6%	-2.8%	-6.8%	-10%	-2.5%	2.4%	11%	-12.6%	-5.6%	-11%	-1.2%	-4.3%	3%	-5.5%
BOGA 3	59%	-0.8%	-18%	1.2%	12.9%	7%	7.7%	-7.1%	-21%	2.0%	0.0%	9%	-12.1%	-2.7%	-11%	1.6%	-3.0%	-2%	-2.2%
BOGA 4	50%	-4.6%	-10%	-3.5%	-	-	-	-9.4%	-17%	-2.2%	0.2%	8%	-10.9%	-4.7%	-10%	-0.6%	-5.3%	2%	-6.1%

[1] For each test, it is mandatory to consider energy saved or used to/from the battery. The column “Fuel + SoC compensation” includes Fuel from the combustion engine as well as Electrical energy consumed/stored. For this compensation a simple correction method has been used that directly calculates the equivalent amount of fuel that corresponds to a certain SoC difference (where this difference is defined as “accumulated SoC – used SoC” during the test).

Obviously, in this particular setting, one MJ of electrical energy seems to deliver more displacement than one MJ of diesel fuel. For this reason, an attempt has been made to correct for this difference and to determine the amount of fuel that would be equivalent to a given SoC change. Neglecting transmission efficiency differences it is assumed that fuel energy is transformed into kinetic energy with a 40 % efficiency while electrical energy is transformed with an overall efficiency of 95 %. This correction effect is negligible for the some tests (in view of the small net ΔSoC), but more visible in the BOGA tests presented in Table 1.

3. Assessment Results

When taking into account all configurations of the TRANSFORMERS improvement measures, a large set of measures is generated: eight configurations for aerodynamics, three for hybrid and a nearly endless range for loading efficiency. When combined with mission profiles of different speed limit, slope, congestion and payload, it becomes difficult to display and analyse these results. For this reason, in the following sections the effectiveness of all TRANSFORMERS innovations is displayed for a maximum of three different levels: low potential, middle potential and high potential, see below:

- Loading efficiency increase due to double load floor (A)
    - Low potential results: 1ton additional payload
    - Middle potential results: 3tons additional payload
    - High potential results: 5tons additional payload
- Aerodynamic loss reduction due to advanced aerodynamics (B)
    - Low potential results: High-flat + boat-tail
    - Middle potential results: High-tapered + no-boat-tail
    - High potential results: High-tapered + boat-tail
- Fuel efficiency increase due to hybrid on demand (C)
    - Low potential results: 80kW and 20kWh
    - Middle potential results: 160kW and 20kWh
    - High potential results: 240kW and 10kWh

In addition, the combined potential of all technologies is discussed (A+B, A+C, B+C and A+B+C) at low, middle and high potential. The potentials are calculated for different mission profiles at fixed discreet payloads 8t, 15t and 25t. Strictly speaking, the combination of increased loading efficiency of 5t with an initial loading of 25t is not possible, since the max GVW is then surpassed. The option is nonetheless considered, in order to illustrate what the potential would be in case heavier vehicles are authorized to EU roads. The potential of heavier vehicles is assessed in the related European project AEROFLEX.

The current savings potential of TRANSFORMERS technologies is shown in Table 2 below. The configurations (A, B, C) etc. as well as the route type are presented to highlight the range of savings potential.

Table 2.: Current potential of TRANSFORMERS technologies in terms of effectiveness %l/ton.km

road type	urban									motorway																	
topology	flat									flat						hilly			mountain		
congestion	low			medium			high			low			high			medium			average		
payload	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons	8 tons	15 tons	25 tons
[HF+NBT / noHOD]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
A low	-5%	-1%	0%	-6%	-1%	0%	-6%	-2%	0%	-8%	-3%	-1%	-8%	-3%	-1%	-8%	-3%	-1%	-6%	-2%	0%
A med	-18%	-8%	-3%	-19%	-9%	-4%	-19%	-9%	-4%	-22%	-11%	-5%	-22%	-11%	-5%	-22%	-11%	-5%	-19%	-9%	-4%
A high	-27%	-13%	-6%	-28%	-14%	-7%	-29%	-15%	-7%	-32%	-18%	-9%	-31%	-17%	-9%	-32%	-17%	-9%	-28%	-14%	-7%
B low	0%	0%	0%	0%	0%	0%	0%	0%	0%	-3%	-3%	-2%	-3%	-2%	-2%	-3%	-3%	-2%	-1%	-1%	-1%
B med	0%	0%	0%	0%	0%	0%	0%	0%	0%	-3%	-2%	-2%	-3%	-2%	-2%	-3%	-3%	-2%	-1%	-1%	-1%
B high	0%	0%	0%	0%	0%	0%	0%	0%	0%	-5%	-4%	-4%	-5%	-4%	-3%	-6%	-5%	-4%	-3%	-2%	-2%
C low	-5%	-5%	-4%	-6%	-5%	-4%	-6%	-6%	-5%	0%	0%	-1%	-1%	-1%	-2%	0%	-1%	-2%	-6%	-6%	-6%
C med	-12%	-11%	-9%	-12%	-11%	-10%	-13%	-12%	-10%	-1%	-2%	-2%	-2%	-3%	-3%	-1%	-2%	-3%	-10%	-12%	-12%
C high	-19%	-17%	-15%	-19%	-17%	-15%	-19%	-18%	-16%	-2%	-3%	-3%	-3%	-4%	-5%	-2%	-3%	-4%	-12%	-15%	-17%
A+B	-5%	-1%	1%	-5%	-1%	0%	-6%	-1%	0%	-10%	-5%	-3%	-10%	-5%	-3%	-10%	-5%	-3%	-7%	-3%	-1%
A+B	-18%	-8%	-3%	-19%	-8%	-4%	-19%	-9%	-4%	-24%	-13%	-7%	-24%	-13%	-7%	-24%	-13%	-7%	-20%	-10%	-4%
A+B	-27%	-13%	-6%	-28%	-14%	-7%	-29%	-15%	-7%	-35%	-21%	-12%	-34%	-20%	-12%	-35%	-21%	-12%	-30%	-16%	-8%
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B+C	-12%	-11%	-9%	-12%	-11%	-9%	-13%	-12%	-10%	-4%	-4%	-4%	-5%	-5%	-5%	-4%	-5%	-6%	-12%	-13%	-13%
B+C	-19%	-17%	-15%	-19%	-17%	-15%	-19%	-18%	-16%	-7%	-7%	-7%	-8%	-8%	-8%	-8%	-8%	-9%	-16%	-19%	-19%
A+B+C	-10%	-5%	-3%	-11%	-6%	-4%	-11%	-7%	-4%	-10%	-6%	-4%	-11%	-6%	-4%	-11%	-7%	-5%	-13%	-9%	-7%
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A+B+C	-39%	-27%	-19%	-40%	-28%	-20%	-41%	-29%	-21%	-37%	-24%	-16%	-37%	-24%	-17%	-37%	-25%	-17%	-42%	-31%	-24%

The potential of the combined features, particularly hybridization, is largest when the cycles are more transient; namely the urban and hilly cycles. Table 3 illustrates a condensed summary of the potential of the technologies. Table 4 highlights the business potential for the hybrid on demand and aerodynamic features.

Table 3.: Potential for Combined Innovations

FC in %/tonkm	Congestion	Payload	Hybrid-on-Demand + Aerodynamic		
			+ 1 ton extra	+3 ton extra	+ 5 ton extra
Urban	Average	15 ton	**-20%**	**-26%**	**-30%**
Motorway: flat	Average	15 ton	**-12%**	**-19%**	**-25%**
Motorway: hilly	Average	15 ton	**-13%**	**-20%**	**-26%**
Motorway: steep hills	Average	15 ton	**-22%**	**-28%**	**-33%**

Table 4.: Combined effects of optimal HoD and aerodynamic (High Flat Tapered + Boat tail)

	Urban/flat	P&G short distance		P&G long distance	
Kkm/year	50 kkm	100 kkm	200 kkm	100 kkm	200 kkm
FC impact [/ton.km]	-26 %	-22 %	-22 %	-17 %	-17 %
Total annual savings [€/yr]	4 k€	4 k€	8 k€	6 k€	11 k€
NPV [€] - 8 yr 4% int.	27 k€	26 k€	52 k€	39 k€	77 k€

When considering the results against the original goals of the project in terms of energy use reduction, the following was concluded:

- The Hybrid-on-Demand system shows highest potential with a relatively small battery (10 kWh) and a large electric machine (motor-generator) (240 kW). The short term regeneration potential determines the potential reduction in energy use, meaning that the highest savings can be reached in urban areas with high traffic dynamics, and with frequent and steep elevation changes. In these situations, the savings potential is up to 18%, where flat and slightly hilly routes show a potential of up to 4%.

- The aerodynamic measures are obviously not effective at low speeds, i.e. in urban situations. The savings potential of the boat tail is up to 3%, which equals the saving potential of the configurable roof. The combined savings are up to 6.5%. The goal of 8% is in reach, and it has to be noted that the impact of the optimized side wings and bulkhead are not included the results.
- The load optimisation measures show a wide variation in the energy use reduction potential. The additional floor space allows for 1 additional pallet, resulting in 3% reduction of energy use per tonne*kilometres. The double floor potential is dependent on the type of cargo. When assuming up to 5 tonnes additional cargo, the energy use reduction compared to an original cargo payload of 8 tonnes is up to 31%. In case of an original cargo payload of 15 tonnes, the energy use reduction is up to 17%.
- Combining all TRANSFORMERS innovations a reduction in energy use/tonnes*kilometres of goods transported of more than 25% can achieved for almost all mission profiles at average payload (15t). At higher payloads, the savings are lower, and at lower payload the savings are higher. In a largely level motorway scenario, the savings at an average payload of 15 tonnes is 24%. On all other routes, the potential is higher and up to 31%. These savings are achievable with optimum system configurations and conditions, i.e. a large electric machine and a "small" battery pack (240kW/10kWh vs 80/20 tested), full use of the aerodynamic measures (high tapered + boat tail), and 5 tonnes extra payload due to loading efficiency improvements.

4. Conclusions and Discussion

The TRANSFORMERS project assessment presented in this paper, concluded:

- 25% overall savings can be reached through selected combinations of measures
- Combined effects of optimal aerodynamic and HoD configurations for constant conditions
- Efficient loading varied from +1 to +5 tons extra

The business case calculations above show for three use cases and three different scenarios (low, middle and high potential), that fair amounts of savings can be achieved with TRANSFORMER technologies under real-life operation. Whether or not this leads to a valid business case depends on the technology costs of course. These have not been inventoried in this project since current costs are associated to a demonstrator and no serial product. For this purpose, the NPV of single and combined technologies has been calculated under certain assumptions of the lifetime and the fuel and driver costs:

- For aerodynamic measures, under the best considered use case, the NPV is equal to 21 000 €. Conditions: short distance international transport, 200kkm per year. This savings is valid for the high-tapered roof and the boat tail.
- For hybrid measures, under the best considered use case, the NPV is equal to 34 000 €. This is valid for the largest configuration (240kW/10kWh) and taking into account long distance international transport, 200kkm per year.
- The highest NPV for loading efficiency is 43 000 €. This is the case for long and short distance international transport, where loading and unloading locations are far away from each other, 200kkm. For the urban round trip, the NPVs are negative. This means, since the loading and unloading locations are so close to each other, the fuel savings to not weigh up against the additional driver/expedition worker costs that are needed to load and unload the truck.
- Altogether, the best use case for combined TRANSFORMERS innovations is the long distance international transport, when considering the optimal configuration of the truck. The NPV is then equal to roughly 70 000 €. In this case, all technologies profit from the large amount of annual

mileage (200kkm) which means technologies pay off quicker. The loading efficiency profits from large distances between loading and unloading locations which means the additional loading/unloading time is stretched out over the operation of the vehicle. At high speeds on the motorway, aerodynamic measures achieve their highest savings. Strictly speaking, this use case is not the best operation for hybrid technologies. However, when hilly and steep hills are included in the mission profiles this is beneficial. Even at lower fuel savings potential of the HoD, the business case can still be positive, since high mileages compensate this effect.

Future savings potential of TRANSFORMER technologies

Further extensions to the TRANSFORMERS approach were anticipated towards the 2050 targets to realise a 60% reduction in CO2 relative to 1990 [6]. In order to investigate the future potential of TRANSFORMER technologies, new calculations were performed. For these calculations, the additional weight penalties of aerodynamic and hybrid measures were reduced. In the case of hybrid measures, the battery density was assumed to be 10kg/kWh (instead of 30kg/kWh). For aerodynamic measures, no additional weight was considered. The additional weight of the double load floor was kept intact.

Potential of the HoD system (C)

For the optimal configuration (10kWh and 240 kW), the potential is max 1% higher: 19-20%.

Aerodynamic loss reduction due to advanced aerodynamics (B)

The weight reduction of aerodynamic components results in nearly no additional benefit. The weight penalty of the current system design was already assumed to be low: 180kg. The reduction of this weight has fairly little effect.

Loading efficiency increase due to double load floor (A)

At this point, no further weight reductions were assumed for the future potential of loading efficiency.

Combined effects (A+B, A+C, B+C, A+B+C)

Similar as above and taking into account the weight reduction of the HoD and aerodynamic measure, the max savings potential to be gained from TRANSFORMER innovations at an average payload of 15t is equal to about 31%.

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