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TRANSFORMERS
Test Drive Results of a new Hybridisation Concept for Truck-Semitrailer Combinations

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Abstract

This contribution is based on results obtained in the collaboration project “TRANSFORMERS”, which has received funding from the European Commission in the FP7-programme. The project has the objective to reduce CO_2 emissions per tonne·km by up to 25%, by improved reconfigurable aerodynamic measures, by innovative loading efficiency measures and by a hybrid-on-demand driveline for truck-semitrailer combinations. Besides giving insight to the overall project, this publication focusses on the trailer mounted hybrid-on-demand (HoD) driveline. This electric driveline is combined with a conventionally propelled tractor unit, effectively hybridizing the combination with minimal changes to the tractor. The objective is to save fuel both in long haulage applications and urban dense traffic scenarios. Test results obtained in both test track and public road testing show that an actual fuel saving of up to 12% can be achieved.

Keywords: CO_2-Reduction; Hybridisation; Energy Efficiency; Environmental Impact

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Nomenclature

EBS	Electronic Braking System	SoC	(Battery) State of Charge [%]
EMG	Electric Motor Generator	TDMS	Trailer Drivetrain Management System
ESU	Electric Storage Unit	TEMS	Trailer Energy Management System
HoD	Hybrid on Demand	VEMS	Vehicle Energy Management System
GCW	Gross Combined Weight	VCU	Vehicle Control Unit
ICE	Internal Combustion Engine	VDC	Vehicle Dynamics Control

1. Introduction

In today’s economy goods transportation on road is the most important mode of transport in Europe, Shell (2016). The vast majority of these transports use diesel powered trucks, although alternative propulsion systems are investigated, especially for inner city distribution. Within these boundary conditions the European Commission set a target CO_2 reduction of 60% by 2050 in its White Paper on Transport Efficiency, European Commission (2011). This target becomes even more challenging, when considering the estimated growth in transport, Shell (2016). Achieving this goal requires a considerable increase in both load efficiency as well as fuel efficiency. The TRANSFORMERS project targets both aspects.

While present truck-trailer combinations perform a wide variety of transportation tasks with a fixed design, future vehicle combinations could be easily adapted to the specific needs of each load and transport mission. TRANSFORMERS achieved this with the following innovations:

- A distributed, modular, and mission adaptable Hybrid-on-Demand (HoD) driveline concept that is applicable to both, legacy and future trucks
- A pre-standard electric HoD Framework that supports a broad market introduction of hybrid commercial vehicles and provides planning certainty for future Research Technology & Development (RTD) activities
- Mission-based configurable aerodynamic overall truck-trailer design
- Load efficiency optimized trailer interior design

TRANSFORMERS focussed 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.

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.

In the project two innovative semitrailers were developed and tested. The Load Optimisation Trailer will not be discussed in this paper. The present publication focusses on the Hybrid-on-Demand driveline in the Energy Efficiency Trailer that was built by Schmitz Cargobull. Because 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). Fig. 1 shows one combination during public road testing.

Fig. 1 TRANSFORMERS Truck-Semitrailer combination during public road testing

The requirements and evaluation metrics from an end user perspective were discussed in a previous paper, Hariram et. al. (2014). The mechanical integration of the HoD driveline is described in Meurer et. al. (2015). 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. (2017), and will be repeated here to the extent necessary. The effect of such new vehicle concepts on existing safety barriers is discussed in Schwedhelm (2018).

The scope of this publication is the evaluation of the fuel savings achieved by the HoD driveline under different driving conditions. Testing on public roads and test track for long haulage and urban dense traffic scenarios were carried out to show the effect of the developed concept.

2. System Architecture

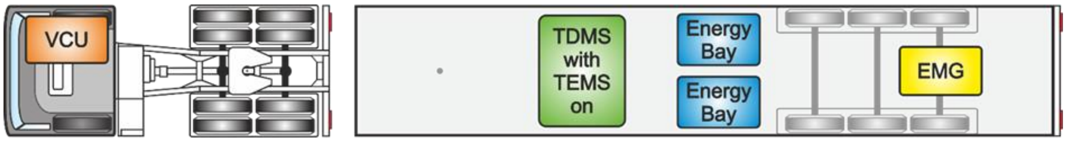
The system architecture considers the whole combination of the truck and semitrailer equipped with an electric driveline. Early in the project the need of a minimal communication between the truck and the trailer was identified, while other projects aim at a “semitrailer only”-solution, e.g. Gehm (2016) and Eckert et. al. (2017). Fig. 2 shows the both cases considered in the TRANSFORMERS project. Case A shows the structure of the demonstrator vehicle representative for legacy situations in which the HoD-trailer is coupled to a largely standard truck with uni-directional communication to the trailer. The Trailer Drivetrain Management System (TDMS) uses its internal Trailer Energy Management System (TEMS). The TDMS controls the functionality on the trailer and requests torque from the Electric Motor Generator (EMG). Case B represents future situations, when trucks – especially hybridised trucks – may already include a Vehicle Management System (VEMS) on their own. If the trailer detects such a truck, the TEMS is switched off and the trailer can be used as an electric propulsion and braking device by the truck. The detection is based on the presence or absence of messages from the truck. Case B is expected to increase the fuel efficiency over Case A, because it allows for bi-directional communication and a more integrated energy management considering the whole vehicle combination.

The logical system architecture as defined in the pre-standard HoD-Framework is depicted in Fig. 3. Besides the basic functionality of the TDMS it defines the interfaces between the subsystems and the outside world.

- **VCU-Interface:** The communication interface between truck and trailer with respect to the HoD system.
- **EBS-Interface:** This is the interface to the electronic braking system on the trailer. It is important to ensure both safety and a proper brake blending functionality between service brakes and electric braking, see Meurer et al. (2015).
- **EMG-Interface:** This interface includes the communication between the TDMS and the EMG to control the EMG power flow as well as the electrical interface. This interface is part of the framework to support the development of framework compliant EMGs.
- **ESU-Interface:** This interface includes the communication between the TDMS and the Electrical Storage Unit (ESU) as well as the electrical interface. As with the EMG-Interface, this framework definition shall support the development of framework compliant ESUs, not limited to batteries.

The VCU-Interface and indirectly the EBS-Interface, which provides information from the truck too, handle the communication between the truck and the HoD system. For Case A only a one directional communication from the truck to the trailer is needed, which is based on ISO 11992-2 and -3. Nevertheless, the demonstrator trailer also sends signals to the truck to provide visual feedback for the driver.

Case A: HoD-Trailer coupled to a standard truck



Case B: HoD-Trailer coupled to a VEMS-Truck

Fig. 2 Structures of the HoD-Driveline for Case A and B scenarios

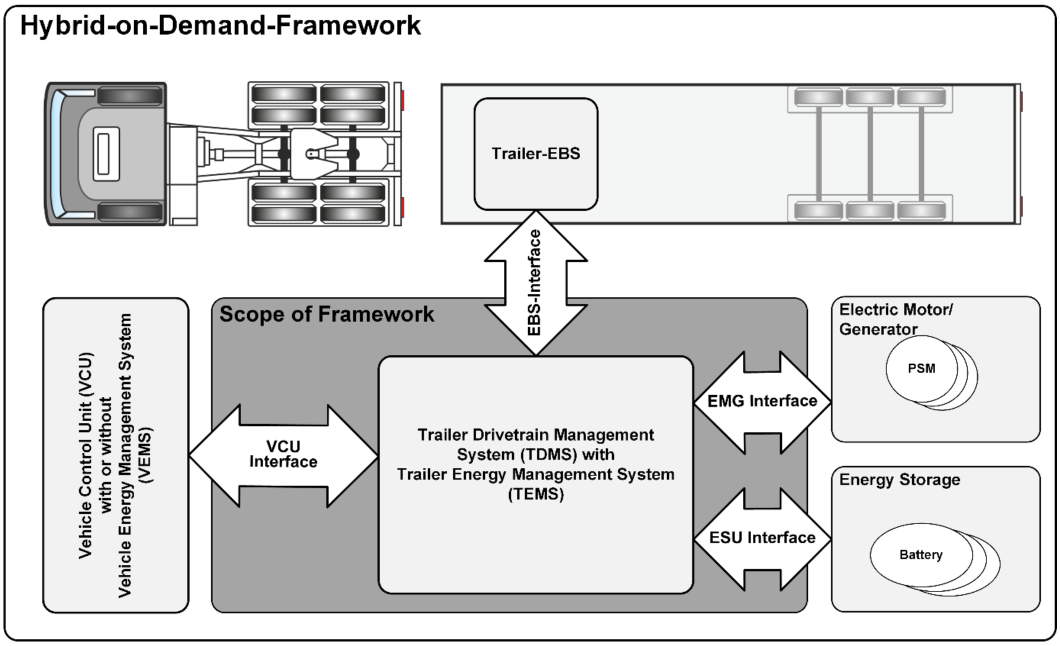


Fig. 3 Logical System Architecture of the HoD-Framework

The truck is operated normally by the driver with standard controls. Electric power is added by the EMG to supplement the power of the truck's internal combustion engine (ICE) under certain conditions, e.g. ESU State of Charge (SoC) and no VDC intervention. When braking, the EBS on the trailer performs a brake blending between electric braking and service brakes without any intervention from the driver. Furthermore, electric braking is applied, when the truck retarder or engine brake is requested by the driver. Endurance braking systems are the preferred method of braking for long haul applications over service brakes, as they reduce wear. Thus, including the electric braking with endurance braking substantially increases the energy recuperation potential. To further increase the recuperation potential a pure electric braking functionality was added, which prevents kinetic energy of the truck being transformed to heat in either service brakes or retarder. Pure electric braking is technically a stretch brake and as such conflicts with current regulations. It would be favorable if future regulations had exceptions from this strict rule for hybrid applications when trailer braking is provided by an electric driveline not affecting the trailer service brakes.

Fig. 4 shows a schematic overview of the driveline components installed in the HoD trailer. Mechanical parts of the drivetrain are the EMG, the transfer box including a clutch, and the differential at the driven axle. The electrical parts are the ESU, the Inverter, and also the EMG. Their combination is currently limited to about 80 kW continuous power. The clutch decouples the EMG from the driven axle,

- to reduce the drag torque of the trailer, when no torque is requested from the EMG, and
- to ensure a safe state of the trailer, when a fault in the HoD system occurs, or the system is switched off.

During the development of the drivetrain, relevant regulations as well as functional safety were considered. For details about the safety concept please refer to Nitzsche et. al. (2017). It needs to be highlighted that the semitrailer cannot drive autonomously – a connection to the truck is necessary to activate the electric drivetrain. The trailer driveline is only supplementary to the conventional tractor driveline.

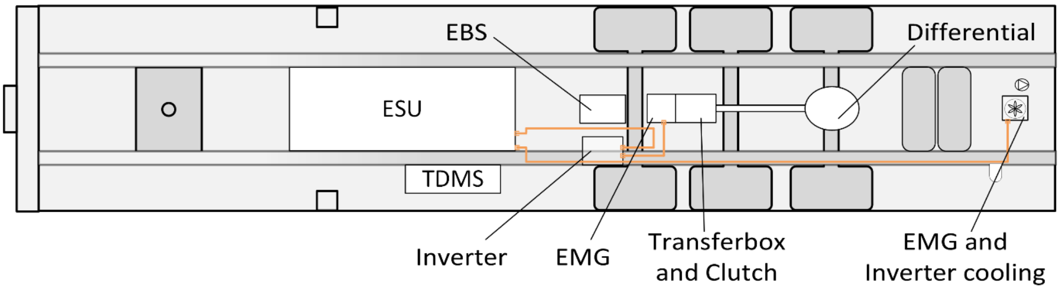


Fig. 4 Top View of the TRANSFORMERS trailer with the location of important components

3. Commissioning and First Test Runs

Commissioning and testing of the TRANSFORMERS demonstrator took place in a number of locations across Europe. Schmitz Cargobull undertook the mechanical integration of the driveline components into the trailer after which it went to the facilities of Fraunhofer IVI in order to install and commission the HoD system. Knorr Bremse developed the brake blending including testing of this important function. Subsequently the HoD trailer was first handed over to Volvo for further fine tuning and safety testing before on road testing in Sweden. Second it was handed over to DAF for testing simulated heavy traffic conditions on test track.

The commissioning followed a stepwise approach, described in Nitzsche et. al. (2017). This allowed for an early start as soon as components were available. After the individual parts were tested successfully, they were integrated in the trailer to build up the complete HoD drivetrain, which then was put into operation under central control of the TDMS. Both tractor units were used during that time to ensure the interoperability.

Special attention was paid to the testing of the functional safety concept prior to the actual testing. A number of experts from different organisations tested the truck-trailer combination under various driving conditions (different road friction coefficients, different loading conditions, etc.) – including vehicle dynamics tests. Various handling, braking and driving tests were undertaken at Volvo to ensure that the combination behaved in a safe and predictable way before the commencement of on-road tests. The vehicle remained safe at all times. When provoking faults, the installed safety measures (mutual checking of ECUs and fault handling strategies) worked as intended. Finally the trailer was successfully registered with the HoD system installed, and the way was paved for public road testing.

4. Testing and Results

The Energy Efficiency Trailer has been subject to a series of tests determining the impact of the HoD system on energy consumption[1]. At the same time these tests generated data used to validate a detailed vehicle simulation model. Two separate test programs were run. First, a Volvo tractor was combined with the trailer and driven on public roads in Sweden with the aim to investigate operation on typical long haul routes including motorways. Second, a DAF tractor was combined with the trailer and tested on the DAF test track to investigate operation in conditions that simulate haulage truck operation in dense (urban) traffic conditions. This section only can give a brief overview of the testing. Details and simulation results can be found in the final report, Van Zyl et. al. (2017).

Besides the hybrid drivetrain, the Energy Efficiency trailer is equipped with aerodynamic measures. This includes a curved front bulkhead, side skirts, a roof whose shape can be changed by varying the height both at the front and the rear of the trailer and it has a boat tail that folds in/out. The present tests focus on the hybrid drivetrain. Thus, the roof was kept flat and at maximum height (4.0 m). The tractor roof deflector was set for lowest drag with the trailer. Tyres were new at the start of the testing. Results of the aerodynamic measurements are included in the final report, Van Zyl et. al. (2017).

4.1. Public Road Testing – Long Haul Scenarios

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, 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.

Two representative routes were selected: BOGA and BOB. BOGA is a 129 km long route and is a mix of country road and motorway. BOB is a 262 km long route with low traffic (back and forth) on motorway E4. The altitude profile of both routes is shown in Fig. 5.

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[1] Although energy cannot be consumed but only transformed, this term is used to emphasize the energy flow from the sources (fuel and electric energy) to waste heat (engine, brakes, etc.).

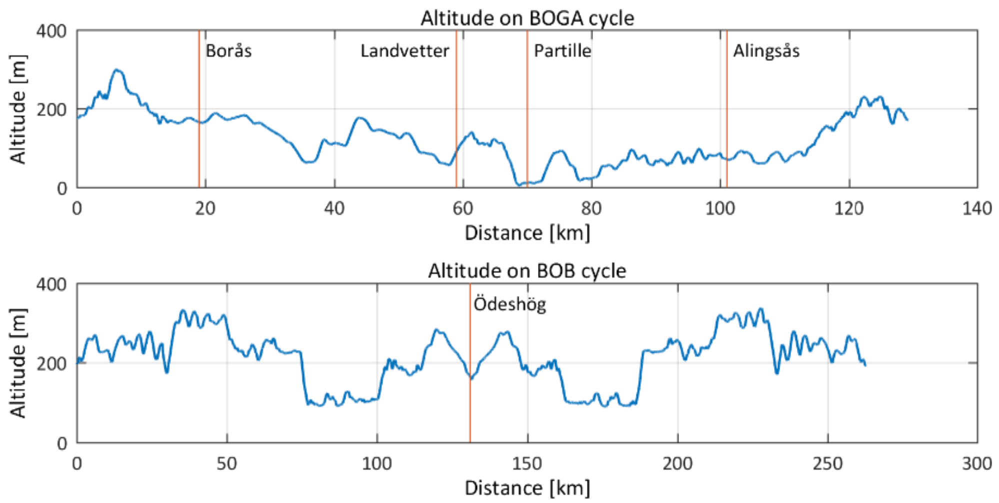

Fig. 5 Elevation profile of Volvo test routes. top: Borås – Landvetter (Göteborg) – Partille – Alingsås – Borås (BOGA); bottom: Boräs – Ödeshög – Borås (BOB)

Table 1 Volvo test programme with various loading conditions, HoD system status and number of test runs

Vehicle configuration				Test route	
Boat tail	GCW [tonne]	Payload [tonne]	HoD system	BOGA	BOB
Out	39	26	Off	2	2
Out	40	27	On	4	3
Out	27	14	Off	-	2
Out	28	15	On	-	2

Table 1 gives an overview of the different fuel consumption tests that were performed and of the corresponding payload. As shown tests were done at two nominal payload levels: at the maximum level corresponding to a nominal GCW of 40 tonne, and at the average European cargo level of 15 tonne. To simulate the operation of a trailer without HoD system, HoD was switched off (and unclutched) and the HoD system weight penalty was compensated by reducing the payload with 1 tonne. A normalization vehicle is used to cancel out changes in external conditions between test runs, e.g. weather. This state of the art approach minimizes the error of the measurements and allows reducing the number of necessary test runs.

Fig. 6 shows data obtained in these tests and illustrates the operation of the HoD driveline. The results are for the BOB tests while driving with a 40 tonne GCW. In these tests repeatability was higher because traffic density was low and cruise control could be kept on all the way, as evident from the speed profile of the TRANSFORMERS combination and of the lead normalization vehicle. It can be observed that the HoD driveline goes through consecutive periods where SoC decreases, because driving energy is supplied, and periods of SoC increase resulting from braking energy recuperation. As the vehicle speed is almost the same as with the HoD switched off, the electric driving power supply fully relaxes the power demand from the combustion engine and this reduces diesel fuel consumption. After around 100 km of driving the battery SoC level has reached a lower limit (around 30 %). From then on further electric power supply has to wait until some braking energy has been recuperated and fuel savings become fully dependent on the route topology (barring influence of traffic). As shown in Fig. 6, even in this condition, significant fuel savings occur when comparing with the HoD off situation. Fig. 6 also shows that with this topology, SoC levels at the start and at the end of the trip are similar, making this a robust measurement result. Small differences in SoC start level were found to have little impact and similar results were obtained with a 15 tonne payload.

The HoD functionality is illustrated in some more detail in Fig. 7. This figure corresponds to a portion of the BOGA cycle between Partille and Allingsås. This figure shows trip altitude profile and electromotor torque as well as HoD clutch engagement. The maximum EMG torque during propulsion was limited to 50% of the maximum to balance the recuperation phases. In the braking phases shown, the EMG reached its maximum power, which also limited the torque applied.

With the measurement results the energy consumption benefits of the HoD driveline have been calculated for the different test cases. For determining of battery energy supply/recuperation and of total energy consumption, changes in battery SoC and fuel consumption values were converted into MJ. This was based on the nominal battery capacity of 22 kWh and on a fuel lower calorific value of 35.72 MJ/l.

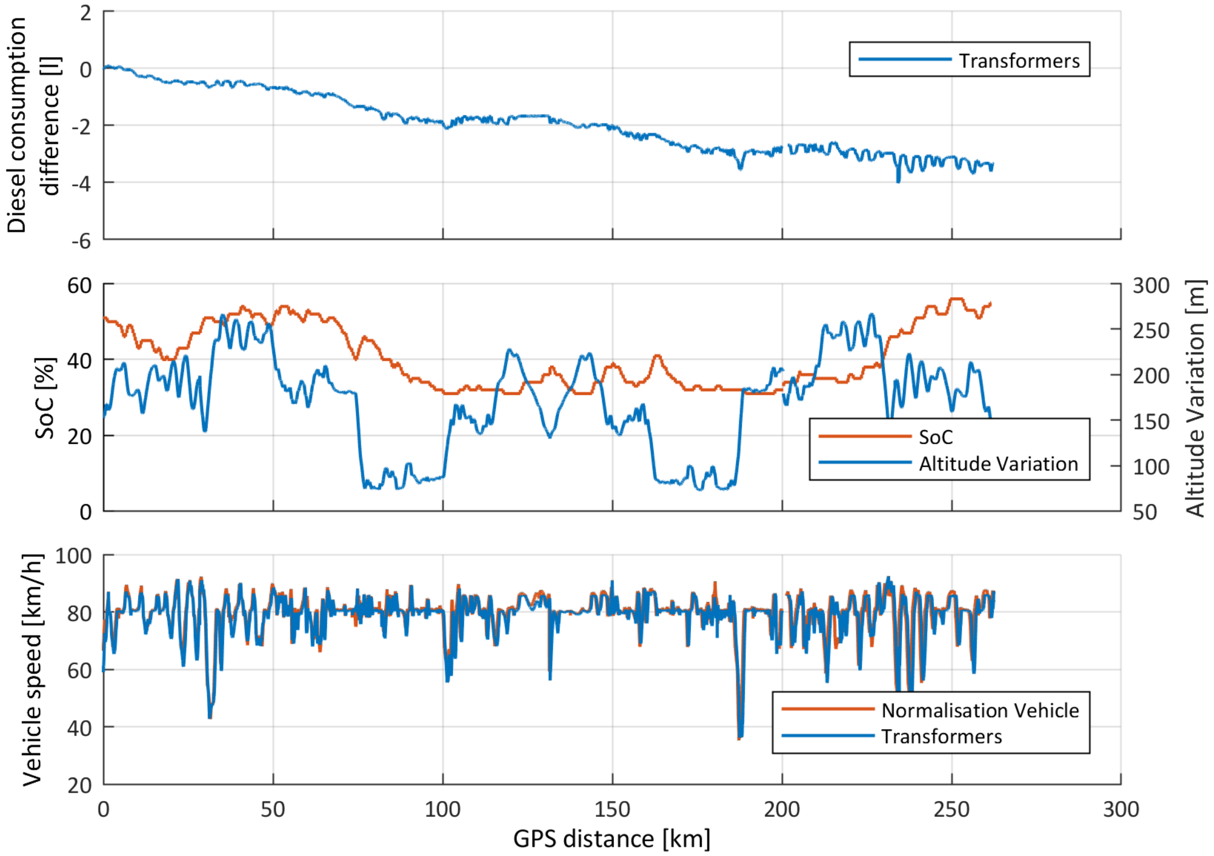

Fig. 6 Illustration of HoD operation; BOB test with 40 tonne GCW; speed profile mean standard deviation between normalization vehicle (Ref FH1758) and the Transformers vehicle under test: $\sigma = 1.5$ km/h

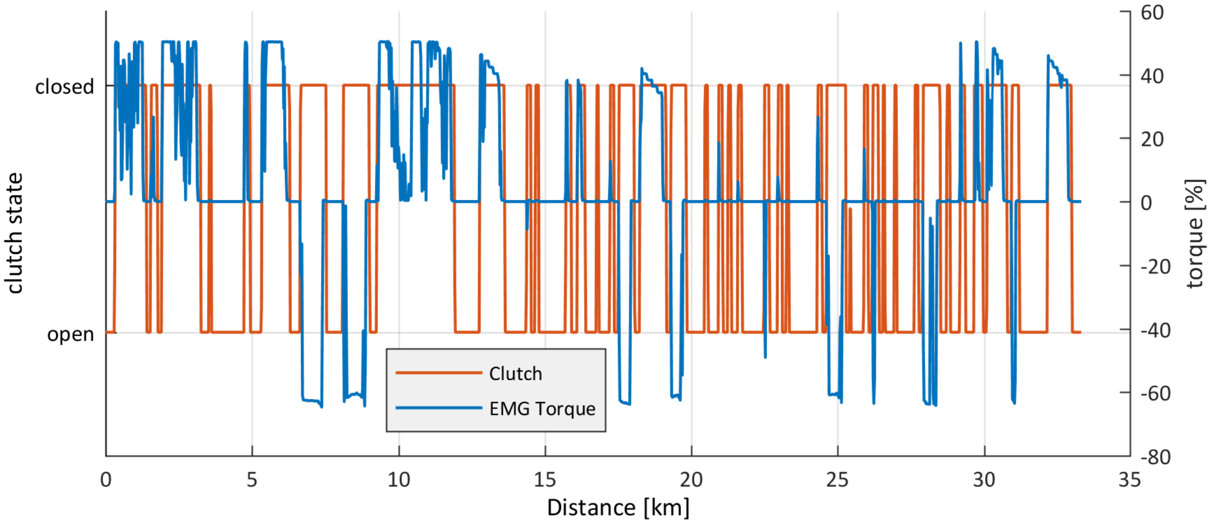

Fig. 7 Illustration of HoD clutch engagement and EMG torque variation; BOGA test with 40 GCW (negative torques correspond to braking and thus SoC increase)

From the BOB test results shown in Table 2 it is clear that there is a significant reduction in the fuel demand with the HoD system on. Since the net ΔSoC between start and end of the trip was quite small, total electric energy supplied by the battery was almost equal to the electric energy recuperated during braking events[2]. Net energy consumed for propulsion was reduced (on average) with 3.2 % for 40 tonne GCW and with 2.3 % for the 15 tonne payload situation. These savings are obtained without draining the battery from start to finish. Higher fuel savings could be achieved when starting with a full and stopping with an empty battery. The traction energy demand is then partially fulfilled by electrical energy from the grid, asking for charging of the battery at given intervals. The TRANSFORMERS demonstrator does not rely on external battery charging, although the HoD-Framework also supports plug-in concepts.

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. 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 %. To be fair both are somewhat optimistic. This correction effect is negligible for the BOB tests (in view of the small net ΔSoC), but more visible in the BOGA tests. These are summarized in Table 3.

Clearly considerable overall savings are observed, but with more scatter between the measurements (linked to a stronger variation in speed profile because the cruise control was not on all of the time). Fig. 8 gives more details on the (equivalent) diesel savings in the different sections of the BOGA cycle.In this figure the energy changes for the different sections of the BOGA cycle are summarized. For the Borås-Landvetter motorway section savings are larger than in the other motorway section (Partille-Alingsås). Clearly, HoD benefits change with route topology. They will also change with HoD control settings. In fact, Fig. 8 also mentions data for the BOGA3 test where an unsuccessful attempt was made to increase fuel savings by manual interaction with the HoD control. All of the other results were obtained with the following HoD control settings: (1) braking is automatically engaged when Volvo engine brake (VEB) is active; (2) EMG torque ramps up linearly from 0 to 100 Nm between 20 and 30 % driver torque demand; then remains 100 Nm until 80 % driver torque demand and finally ramps down linearly towards zero at 90 % torque demand.

Table 2 Test results for the BOB tests; 40 t GCW (25 t payload) and 15 t payload, see Table 1

Vehicle configuration	Diesel consumed [l/100 km]	Battery energy supplied [MJ/100 km]	Battery energy recuperated [MJ/100 km]	Net energy consumed [MJ/tonne·km]	Equivalent Diesel consumed [l/100 km]
40 t HoD-off 1	35.90			0.513	
40 t BOB-1	34.87	31.7	32.6	0.498	34.72
40 t BOB-03	34.71	31.7	33.0	0.495	34.55
15 t HoD-off 1	30.38			0.724	
15 t HoD-off 2	30.28			0.721	
15 t BOB 01	29.58	25.0	27.1	0.704	29.21
15 t BOB 02	29.71	28.1	25.1	0.707	30.21

Table 3 Test results for the BOGA tests; 40 t GCW, see Table 1

Vehicle configuration	Diesel consumed [l/100 km]	Battery energy supplied [MJ/100 km]	Battery energy recuperated [MJ/100 km]	Net energy consumed [MJ/tonne·km]	Equivalent Diesel consumed [l/100 km]
HoD-off 1	37.56			0.536	
HoD-off 2	37.01			0.529	
BOGA-01	35.39	37.4	35.0	0.521	35.60
BOGA-02	36.09	36.1	36.1	0.530	36.09
BOGA-04	35.57	40.4	33.5	0.524	36.15

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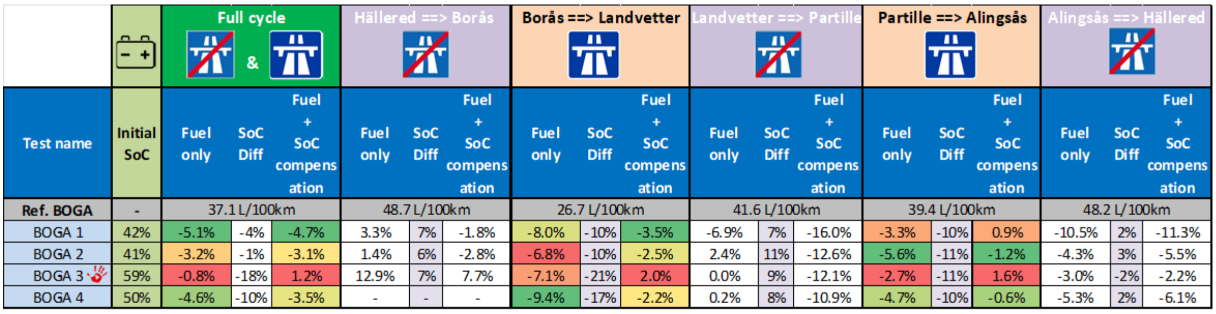
[2] It is worthwhile pointing out that SoC-level determination is subject to up to 5 % error (equivalent to 4 MJ). This, together with the non-ideal repeatability of the tests make it difficult to draw more detailed conclusions.



		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%

Fig. 8 Fuel savings with HoD in different extra-urban and motorway parts of the BOGA test runs

Limited testing was done with an alternative strategy, in which the ECO-roll function was replaced with brake energy recuperation. This modification substantially increased the energy savings for a part of BOB and for the motorway parts of BOGA. But due to the limited testing with this configuration no conclusive results could be obtained. Nevertheless, further investigation of this strategy seems promising.

4.2. Test Track Testing – Simulated Heavy Traffic Conditions

Operation of the Energy Efficiency Trailer in simulated heavy traffic conditions was tested by DAF on their test track. For this a representative speed versus time profile had to be identified. Examples of dense/urban traffic speed profiles in the literature are the “US Highway 65” cycle or the “Suburban” profile (both used in the US Smartway program) or the urban part of the WHTC cycle. These profiles are however highly dynamic and difficult to repeat on a track. For this reason it was decided to develop a more stylized speed versus time profile that is based on heavy-duty on-road monitoring. This profile is shown in Fig. 9. To perform one test with the required length, the vehicle needed three rounds on the high speed (oval) test track at DAF. For maximum reproducibility vehicle speed control in these tests was automated via a MicroAutobox.

Fig. 9 shows that reproducibility was indeed high ($\sigma = 0.7$ km/h). As with Volvo, testing at DAF followed an internal procedure related and similar to SAE J1321. Fuel consumption was not measured directly but calculated from ECU-data; experience (and calibration) with this approach at DAF indicated a better than 1% accuracy.

The test program and corresponding results are summarized in Table 4. Tests were performed in batches of (typically 5) consecutive repeat runs. Batches with HoD on alternated with batches with HoD off. Payload was increased for measurements that simulate a vehicle combination without HoD (HoD off) like for the Volvo tests. Table 4 gives both total energy saved (with electric and fuel energy savings weighed equally) as well as diesel equivalent savings (electric energy savings are converted into diesel savings as explained above) and the corresponding standard deviation. These results indicate that in heavy-traffic conditions, savings tend to be even higher than in the motorway tests. The low standard deviation shows the significance of the results. All of these tests were obtained with the default HoD control settings; no tests were performed with the alternative HoD control settings. SoC levels at the start of the test run batches varied between 50 and 62 %.

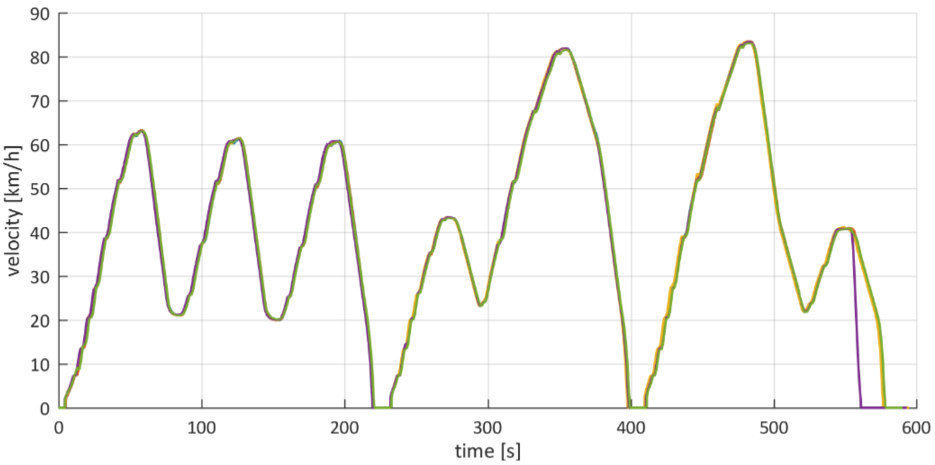


Fig. 9 Five consecutive speed profiles, simulating urban dense traffic conditions at DAF test track; one aborted around 550 s

Table 4 DAF test program and main results

HoD	Payload [tonne]	Valid runs	ΔSoC [%]	Δ diesel [l]	Standard deviation [l]	Total Energy saved [%]	Equivalent Diesel saving [%]
off	0	4+4		2.14	0.073		
on	1.2	4+4	2.25	1.88	0.078	6.6	12
off	15	4+3		3.31	0.041		
on	16.2	4+4	-1.9	3.21	0.119	5.9	3

5. Summary

The TRANSFORMERS project followed different approaches in order to increase transport efficiency in order to help reduce CO_2 emissions. Besides aerodynamic measures and loading efficiency improvements, a prototype Hybrid on Demand (HoD) driveline and its corresponding trailer based control architecture has been designed, built and successfully integrated in a trailer. The compatibility of this trailer and its newly developed communication interfaces have been demonstrated with two OEM tractors; one each from Volvo and DAF. These combinations have proven a good and safe driving behaviour. The trailer complies with current regulations and was successfully registered.

The performance and fuel efficiency of the Volvo vehicle combination has been tested on the road in Sweden in real-world fuel measurements that are representative of long haul missions. With the DAF vehicle combination this technology has been tested in a dedicated test cycle that is representative of haulage truck operation in dense urban traffic conditions. With a relatively simple non-optimized control setting for the HoD system, a significant fuel saving was realised, often exceeding 3 %, which is also confirmed by the simulations. Further optimisation is expected to yield considerably higher savings. Simulations showed that higher E-machine powers and smaller battery sizes (weight) improve the fuel saving. Even more savings are to be expected when HoD control can be combined with the tractor VCU control towards an integrated energy management, leveraging the full potential of the system. It needs to be highlighted that the fuel savings are SoC-compensated. They do not rely on draining the battery from start to finish. With plug-in concepts even higher fuel savings can be achieved, but charging time is required then to make use of this potential.

These results show that this TRANSFORMERS innovation is a realistic and important enabling technological solution to meet with the ambitious EU CO_2-reduction targets for transportation.

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