TRANSFORMERS - Configurable and Adaptable Trucks and Trailers for Optimal Transport

Paul Adams, Gunter Nitzsche, Sofia Lofstrand, Alfredo Selas, Guus Arts, Adewole Adesiyun, Sebastian Wagner, Thorsten Koch, Bernard Jacob, Franziska Schmidt, et al.

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

TRANSFORMERS – Configurable and Adaptable Trucks and Trailers for Optimal Transport

Paul Adams [a,*], Gunter Nitzsche [b], Sofia Löfstrand [a], Alfredo Selas [c], Guus Arts [d], Adewole Adesiyun [e], Sebastian Wagner [b], Thorsten Koch [f], Bernard Jacob [g], Franziska Schmidt [g], Marc Billiet [h], Adi Hariram [i], Birger Queckenstedt [j], Gertjan Koornneef [k], Cor van der Zweep [l], Ton Bertens [m], Bernhard Hillbrand [n]

[a] *Volvo Group Trucks Technology, Gothenburg, Sweden*
[b] *Fraunhofer Institute for Vehicle and Infrastructure Systems IVI, Dresden, Germany*
[c] *Robert Bosch GmbH, Stuttgart, Germany*
[d] *DAF Trucks, Eindhoven, The Netherlands*
[e] *FEHRL, Brussels, Belgium*
[f] *Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany*
[g] *IFSTTAR, Champs-sur-Marnem, France*
[h] *IRU Projects, Brussels, Belgium*
[i] *Proctor & Gamble, Brussels, Belgium*
[j] *Schmitz Cargobull GmbH, Altenberge, Germany*
[k] *TNO, Helmond, The Netherlands*
[l] *Uniresearch, Delft, The Netherlands*
[m] *Van Eck, Beesd, The Netherlands*
[n] *Virtual Vehicle, Graz, Austria*

Abstract

This contribution is based on the European collaborative project TRANSFORMERS (Configurable and adaptable trucks and trailers for optimal transport), which received co-funding from the European Commission. The project has the goal of reducing energy use per tonne.kilometre of goods transported by up to 25%. This is achieved by innovations including: i) Configurable whole vehicle aerodynamics, ii) Improved loading efficiency measures, iii) A distributed, trailer mounted electric driveline known as “hybrid-on-demand” for truck-semitrailer combinations. The combination of innovations gives the possibility of a semi-trailer combination which can be adapted or re-configured to suit individual transport missions. The paper focuses on providing background to the project, an overview of the innovations developed within the project, and the main conclusions that were drawn from the wide range of work undertaken within the project. It covers both the “Energy Efficiency” and the “Load Optimisation” trailers which were developed and tested within the project.

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

---

* Corresponding author. Tel.: +46-313233982
E-mail address: paul.adams@volvo.com
Project website: www.transformers-project.eu

Nomenclature

EMG	Electric Motor Generator
HoD	Hybrid on Demand
KPI	Key Performance Indicator
SoC	State of Charge

1. Introduction

Current semi-trailer combinations are very much a one size fits all solution, being optimised for a limited number of use cases and for maximum payload. At the same time there is an ever increasing need for transport efficiency to be optimised for each transport mission. The TRANSFORMERS project has successfully developed and demonstrated a range of innovations to improve transport efficiency for the road haulage industry. The project combines these innovations in easily adaptable semi-trailer combinations so that they can be optimised for each transport mission.

The TRANSFORMERS consortium comprises 13 partners (see Fig. 1) from six European countries, and has received funding under the EU Seventh Framework Programme for research, technological development and demonstration under Grant Agreement No. 605170.

Fig. 1 Overview of Project Consortium

The overall objective of the TRANSFORMERS project is to develop and demonstrate innovative, energy efficient and load optimised semi-trailer combinations for regional and long haul transport missions. By looking at the tractor/ semi-trailer combination holistically to reduce overall fuel consumption while in parallel improving load efficiency, TRANSFORMERS targeted, and achieved, a 25% energy consumption reduction per tonne.kilometre of goods transported in real world scenarios within the existing European regulatory framework. This reduction is targeted without affecting the road infrastructure. It is achieved through the following innovations, whose targets are illustrated in Fig. 2:

- A semi-trailer mounted, distributed "Hybrid-on-Demand" (HoD) electric driveline.
- Mission-based, transformable whole vehicle aerodynamics.
- An internal trailer design offering increased load capacity.
- Mission adaptability to allow optimisation of the vehicle combination for each journey.

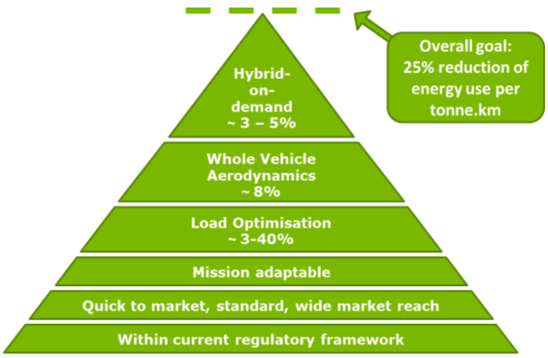

Fig. 2 TRANSFORMERS Targets

This paper addresses the achievements of the project in terms of the overall project goals, namely a 25% energy consumption reduction per tonne.kilometre of goods transported. The paper focuses on the Key Performance Indicators (KPI) related to the impact of the innovations in terms of energy consumption, fuel consumption and CO_2 emission, since these are equivalent to each other and are reflected in the overall goal. Based on this, the economic potential of the innovations is evaluated for a wide array of transport missions, as a basis for business case analyses. This assessment is the basis for a discussion of potential implementation strategies and next steps.

2. End User Requirements

End User Requirements were developed through consultation with an extensive End User Group (see Fig. 3) in addition to an Advisory Group representing all sides of the road transport industry. Successful market acceptance of the TRANSFORMERS innovations is evaluated by comparing the performance against existing state-of-the-art tractor/semi-trailer combinations. The broad End User Group allowed ‘End User’ KPIs to be established for different key performance areas, like Transport Efficiency, Operational Parameters, Vehicle Uptime, Loading Parameters, Safety and Limitations, and Driver Comfort. Rather than evaluating the innovations from a purely technical standpoint, it is based on parameters that affect the road transport businesses which would operate these vehicles. Details of the End User Requirements can be found in Hariram et. al. (2014).

Fig. 3 TRANSFORMERS End User Group

3. TRANSFORMERS Demonstration Vehicles

TRANSFORMERS developed and demonstrated two tractor/ semi-trailer combinations: The Load Optimisation combination and the Energy Efficiency or “Hybrid-on-Demand” (HoD) combination.

The Load Optimisation combination targets increased loading efficiency, and aerodynamics of the complete combination. An internal trailer design for volume limited assignments increases the load capacity within current weights and dimensions regulations. This is achieved through increased inner floor length, and an innovative, multi-section, independently adjustable, double floor system. For transport missions that are weight limited, or for other reasons do not utilise the full volume of the trailer, the trailer features enhanced mission-based, transformable vehicle aerodynamics including side skirts, boat tail and a four segment lowerable roof which can be configured into an infinite variety of shapes (two of which are seen in Fig. 4).

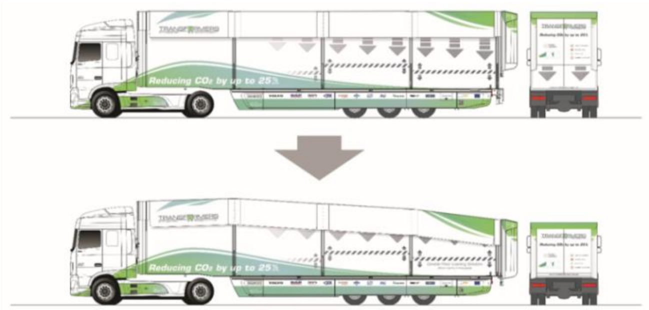
Fig. 4 Load Optimisation Combination with Double Floor Loading System and Aerodynamic Measures (adjustable roof, boat tail, side skirts)

The Energy Efficiency or “Hybrid-on-Demand” (HoD) combination targets reduced fuel consumption through an innovative driveline, and by taking a holistic view of the aerodynamics of the complete combination. The trailer includes a semi-trailer mounted, distributed electric driveline, which is supplementary to the conventional diesel tractor driveline. The HoD driveline is entirely mounted on the trailer, including battery pack, electric machine (EMG), transfer gearbox, drive axle and control system. Electric braking on one trailer axle is used to recuperate braking energy, which is then used to assist the conventional driveline by providing supplementary propulsion from the trailer when certain conditions are fulfilled. The system is based on uni-directional control with limited additional signals sent from the tractor. A pre-standardisation tractor-trailer communication “framework” has been developed to enable market introduction and provide planning certainty for future research activities. This is described in detail in Meurer et. al. (2015) and Nitzsche et. al. (2017).

Furthermore, aerodynamics are addressed with this combination. The combination looks at transport assignments which are weight limited, or for other reasons do not utilise the full volume of the trailer. If the full volume is not needed for payload, the possibility to change the shape of the trailer to improve the aerodynamic characteristics of the complete vehicle is incorporated. The trailer features enhanced mission-based, transformable vehicle aerodynamics including a curved front bulk head, side skirts, boat tail, and a single segment lowerable roof. The roof can be moved into four alternative positions (see Fig. 5), with the tractor roof deflector adjusted to suit.

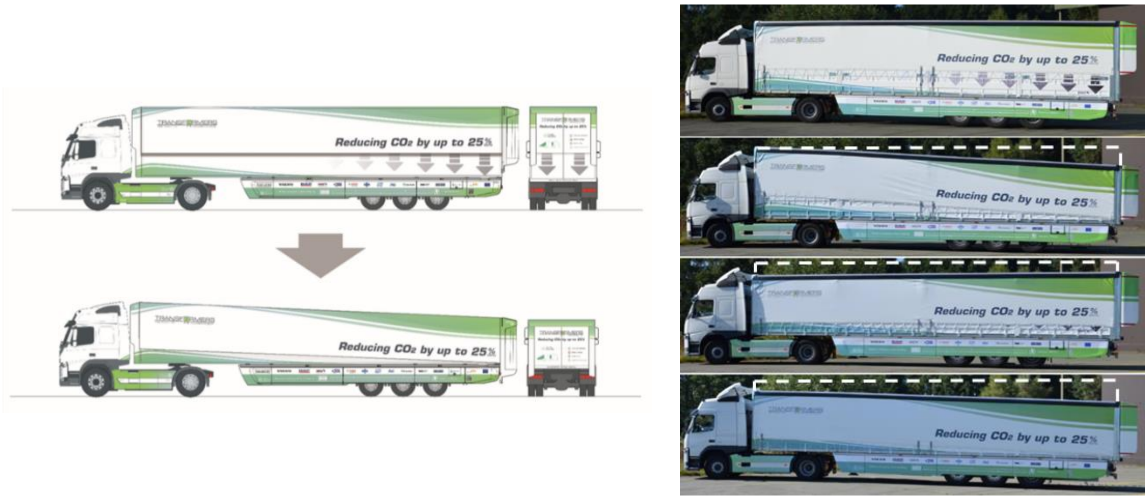

Fig. 5 Energy Efficiency or HoD Combination with Electric Driveline and Aerodynamic Measures (adjustable roof, boat tail, side skirts, etc.)

4. Effect on Highway Infrastructure

It is important to understand the impact of new vehicle combinations and technologies on the highway infrastructure to ensure compatibility, especially with respect to the standards and regulations for the infrastructure and the vehicles. TRANSFORMERS looked at the impact of the innovations on the existing highway infrastructure including pavement loading (Hornych et. al. (2017)), bridge loading (Gonzalez and Schmidt (2017)), impacts with safety barriers (Schwedhelm and Yu (2018)), and dynamic behaviour as it affects highway geometry (Bouteldja et. al. (2017)).

Based on simulations and dynamic measurements taken on the test track, the TRANSFORMERS innovations were not found to have a significantly different impact on the transport infrastructure in comparison to conventional vehicles. Three recommendations were made for amending Directive 96/53/EC on weight and dimensions as amended by Directive (EU) 2015/719:

- The extra tonne allowance for “alternative fuels” should also be applied to articulated vehicle combinations.
- Directive (EU) 2015/719 should provide provisions on the height of the payload centre of gravity (impacts on safety barriers, dynamic behaviour of the truck) and on the longitudinal load distribution, i.e. the balance of axle loads (impact on pavements and on bridges). In this case, the guidance should be targeted at road freight transport operators and shippers on a general, systematic basis, and how compliance could be verified. This should be discussed with the relevant parties.
- Directive (EU) 2015/719 should include a bridge formula, adapted to the European bridge stock allowing the current combinations complying with the Directive 96/53/EC. However, such a formula should remain valid for many years and avoid future combinations inducing increased load effects in existing bridges, which are designed with a life of several decades.

If the European Directive is revised again introducing a maximum GVW for 5 or 6 axle combinations above 40 tonnes, e.g. up to 44 tonnes, 1 tonne should be allocated to “alternative fuels”, and only 3 tonnes for extra payload. If longer combinations such as the EMS are allowed for international transport, the same provision (1 tonne) should be made. Moreover, these combinations should comply with a bridge formula which guarantees that the impact remains acceptable for the existing bridge stock. For details refer to (Jacob et. al. (2017)).

5. Evaluation Framework

In order to assess the project goal of a 25% reduction of energy use per tonne.kilometre, an evaluation framework was defined. The data sources and process steps in the evaluation framework are shown in Fig. 6. The evaluation steps include real world testing, high fidelity simulations, evaluation of the results, and assessment of the economic potential. Based on the vehicle tests and high fidelity simulation results, a consolidated model was used for the final evaluation of the effectiveness of the TRANSFORMERS innovations under various influencing parameters such as road type, payload and traffic conditions. The improvement potential for selected transport missions has been compared to current heavy-duty vehicle technology used for similar assignments. The chosen assessment methods were a trade-off to evaluate the project in terms of fidelity and number of applications assessed. The results will be described in the following sections. Details are presented in Van Zyl et. al. (2017).

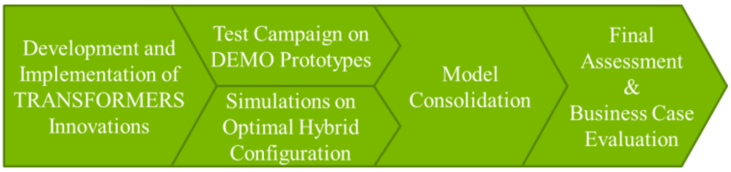

Fig. 6 Schematic of the Final Assessment Procedure

Members of the International Road Transport Union (IRU) highlighted that it is essential to evaluate innovations in different environments as there is no “typical” route for the delivery of goods by road in Europe. Due to the limited scope for real world testing, one of the main indications of benefits delivered by the TRANSFORMERS innovations was obtained from simulations validated against the test measurements. Different scenarios for the evaluation were agreed with IRU and then matched with routes for which data such as heavy goods vehicle speed profiles were available. The scenarios include:

- Motorway driving - flat surface (Scenario S1)
- Motorway driving - mixed environments (Scenario S2)
- Route with frequent elevation changes (Scenario S3)
- Steep hills (Scenario S4)
- Urban driving (Scenario S5)

6. Test Results

The demonstrators have been extensively tested both on the test track and on the road. The following tests were undertaken to provide input to the simulation and evaluation activities:

- Vehicle dynamics test measurements and test driver responses
- Impact on loading efficiency
- Impact of the aerodynamic measures
- Impact of the HoD system in real world conditions (public road, simulated urban heavy traffic)
- The use of load volume sensors was demonstrated

6.1. Safety Testing and Vehicle Dynamics

Safety related testing, including assessment of vehicle dynamics, has been of paramount importance as a key enabler to allow the tests to be undertaken:

- Preliminary theoretical model-based evaluation of the vehicle dynamics
- Commissioning tests
- Functional safety and functionality tests developed together with TÜV Rheinland
- Development and testing of the brake blending functionality
- Internal OEM road approval (braking, handling and HMI aspects)
- Driving dynamics testing to validate the driving dynamics models
- Interviewing of the test drivers regarding driving dynamics

The results showed that the dynamic behaviour is similar to the behaviour of a standard tractor/semi-trailer combination and no additional control measures are needed. The outcome of all tests was positive. In particular all test drivers interviewed perceived the same or better controllability of the TRANSFORMERS vehicle combination in comparison to a conventional combination. Under specific conditions the torque supplied from the HoD driveline was felt to be uncomfortable, revealing that the control software requires further optimisation.

6.2. Loading Efficiency

Loading efficiency tests were undertaken on the Load Optimisation Trailer to investigate the effect of the configurable roof, increased inner floor length and double floor system in terms of ease of docking, loading and unloading. Functional performance was tested in a P&G distribution centre, and was shown to be successful according to the

KPI. The increased inner floor length was shown to successfully allow 34 euro-pallets to be loaded instead of the typical 33. The “flex floor” system was tested successfully and the time to load/unload 4 pallets is approximately 5 minutes when the double floor system is used, compared to approximately 2½ minutes when the double floor is not used. The additional time required for loading/unloading the double floor is used in the economic assessment. The four segment configurable roof was found to take approximately 1 minute to change to a new configuration.

6.3. Aerodynamics

The aerodynamic features of the Energy Efficiency Trailer were tested, using both the DAF and Volvo tractors. The tests were all undertaken on test tracks with the aerodynamic aids in relevant settings, such as boat tail folded in or out, and with various roof configurations. The Volvo tests focused on measuring the fuel consumption benefit of the aerodynamic measures at various constant speeds increasing from 60 km/h. The results show that the fuel consumption can be reduced by 5.7% at 80kph (high tapered roof and boat tail). All results are compared to the reference case of the Energy Efficiency Trailer in the “high flat” position with boat tail folded in. *This means that the results indicated have a “hidden” potential, since gains due to the aerodynamic front bulk head and side skirts are not taken into account.*

In tests using the DAF tractor, the primary goal was to calculate the air drag (Cd*A) of the vehicle combination by measuring the reduced torque required to drive at a constant speed of 90 km/h. During these tests, the boat tail was folded both in and out, along with different roof configurations. The best results were obtained by the roof in the tapered position and using the boat tail: 14.3% air drag reduction. The impact of the boat tail varies depending on the roof position. The air drag results are used for calculations in the evaluation phase.

6.4. Hybrid on Demand Fuel Savings

The HoD system on the Energy Efficiency trailer was tested in simulated urban heavy-traffic conditions on a test track using a DAF tractor, and on Swedish public roads using a Volvo tractor. The results are influenced by the payload, road type, topography and driving cycle dynamics since they influence the energy recuperation potential of the system. After correction of results for the State-of-Charge difference before and after the test, the test results show a reduction in fuel consumption of 5.9 to 6.6% with the HoD system engaged for heavy traffic conditions. On country roads and motorways, the HoD system is dependent on the route topography (elevation changes and gradient). Fuel measurements were undertaken on different Swedish routes, which predominantly have a hilly and low traffic character. In the tests the payload was varied. With 15 tons payload, the fuel consumption reduction on a motorway route is 2.2%. For 40 tonnes GCW (maximum payload), the results vary between 3.3% for a motorway route, to 3.8% for a route with a mix of country road and motorway. More details about the HoD test drive results are provided in Nitzsche et. al. (2018). Alternative control strategies should be investigated, as a short trial at the end of the main testing showed that there could be significant potential for improvement with the current system.

7. Simulations

The simulation model developed during this project consists of different component models coupled together in the co-simulation platform AVL Model.CONNECT to perform holistic simulations. With this method it was possible to include components remotely from different organisations. Variant and case management to aid simulation of a high number of variations was also possible. The HoD component models represent the real HoD system. The tractor components represent a generic tractor. Details can be found in Hillbrand and Weiss (2017).

After the models were validated against the real world test results, the aim of the high fidelity simulations was to determine an optimal configuration to maximise fuel savings potential, by varying key system parameters. This resulted in a high number of variations in a “simulation matrix” agreed within the consortium, and simulated for different route scenarios. The main variations considered were payload, EMG power, and battery size. During the course of the work approximately 700 high fidelity holistic simulations were undertaken.

The results of the high fidelity simulations give a good overview of the potential of several configurations on different types of route, and also served as input to low fidelity evaluation. Increased EMG power (240kW cf. 80kW demonstrated) enabled short term recuperation and gave the best fuel consumption reduction results, while a smaller battery (10kWh cf. 20kW demonstrated) gave better or equivalent results, see Fig. 7. An alternative control strategy was found to offer 1-3% higher SoC corrected fuel savings for the hillier motorway scenarios compared with the system tested. A plug-in scenario does not show improvements for all cases, but offers up to 4% higher fuel savings for some routes. Detailed results can be found in Van Zyl et. al. (2017).

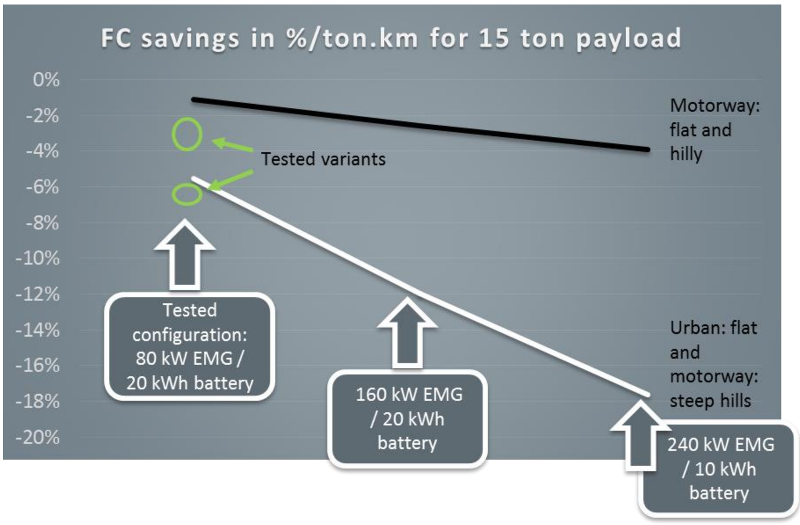

Fig. 7 Fuel saving potential of different HoD configurations based on real world testing and simulations

In summary there is still a high potential for improvements using different control strategies for different route scenarios. More investigation of the optimum system strategy is needed for different routes. The strategy should also consider the possibility of changing EMG torque limits depending on SoC, especially in case of plug-in scenarios. In future, it could be interesting to change the HoD strategy dynamically during driving, to suit the route. Predictive energy management systems could take actual road and traffic conditions into account and would be able to optimize fuel savings.

8. Evaluation

The test measurement results show the potential of individual TRANSFORMERS innovations for a limited number of configurations and test routes. The hi-fidelity simulation results investigated the effectiveness of the HoD under different route conditions, and for variations in the configuration of the system. The evaluation of these results aimed to understand which conditions the innovations perform best on their own and when combined, what are the trade-offs or synergies, and how can optimal savings be assured. The evaluation targeted the impact of the TRANSFORMERS innovations in terms of the key goal of the project: reduced energy use per tonne.kilometre of goods transported. Since the impact on energy use and CO_2 is equivalent to the impact on fuel consumption, the latter is used as the primary metric.

In order to compare and combine the vast amount of results from the tests and the simulations, a harmonised vehicle model is used. This model makes use of a “Willans lines” approach, which describes the relation between the power demand at the wheels and the fuel rate of the engine, Van Zyl et. al. (2017b). The model is calibrated and validated against the high-fidelity simulation results. Loading efficiency is modelled in terms of additional payload that can be carried during the trip.

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

- The HoD 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%, see Fig. 7.
- Aerodynamic measures are not effective at low speeds, i.e. in urban situations. The savings potential of the boat tail is up to 3%, which is similar to the savings potential of the configurable roof. The combined savings are up to 6.5%. The goal of 8% is in reach, and it is 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 potential for energy use reduction. The additional floor space allows for 1 additional pallet, resulting in 3% reduction of energy use per tonne.kilometre. 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 8t is up to 31%. In case of an original cargo payload of 15 tonnes, the energy use reduction is up to 17 %/t.km.

- Combining all TRANSFORMERS innovations a reduction in energy use/t.km of goods transported of more than 25% can be 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 with an average 15t payload, the savings are 24%. On all other routes, the potential is higher, 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 aids (high tapered + boat tail), and 5t extra payload due to loading efficiency improvements.

9. Economic Assessment

The simulation results are used as the basis for the economic assessment. The economic potential of the TRANSFORMERS innovations is evaluated for a number of representative use cases. Since no cost data is used within the project for confidentiality reasons, the assessment is limited to the economic savings derived from the impact on fuel consumption in the evaluation. The evaluation has been done for the three innovation areas separately, as well as when combined.

The economic assessment for three realistic use cases (short distance international transport, long distance international transport, and an urban round trip) and three different scenarios (low, middle and high potential), indicates savings can be achieved with the TRANSFORMERS innovations. Whether or not this leads to a positive business case depends on the technology costs. In general, it can be concluded that the economic savings and net present values (NPV - 8 years) calculated show the potential for a viable business case for all innovations.

The best cases for the different innovations differ. The best use case for the combined TRANSFORMERS innovations is long distance international transport, when the NPV is approximately €70000. In this case, all technologies profit from the large amount of annual mileage (200000 km). The loading efficiency profits from large distances between loading and unloading locations which means the additional loading/unloading time is stretched out over the mission. At motorway speeds, aerodynamic measures achieve their highest savings. Strictly speaking, this use case is not the best case for HoD measures. However, when hilly and steep hills are included in the mission profiles this is beneficial. Even at lower fuel savings potential for the HoD, the business case can still be positive, since high mileages compensate this effect. Detailed results can be found in Van Zyl et. al. (2017).

10. Road Towards Implementation

The TRANSFORMERS innovations that have been developed and demonstrated need further development to enable commercialisation, including:

- Optimisation of components, and especially of the HoD system
- Demonstration of acceptable durability in different conditions, i.e. field testing
- Reducing the complexity and weight of the solutions
- Reducing the cost of ownership of these systems while retaining the targeted functionality
- Ensuring their applicability to as wide a range of applications as possible
- Looking for new features that the TRANSFORMERS innovations can enable

All of these measures will help to improve the market potential of the TRANSFORMERS innovations. This is important because in the beginning, production numbers will be limited with correspondingly high unit costs.

The VECTO tool is to be used in the near future for the assessment of the CO_2 impact of heavy-duty vehicles in certification procedures. The current VECTO proposal is not suited to the CO_2 reduction measures of the TRANSFORMERS concept, because currently only the simulation of vehicles with non-hybrid powertrains and standard truck/ semi-trailer bodywork is included. The VECTO tool, however, is designed to simulate CO_2 emissions based on physical and measured properties of a complete heavy duty vehicle. This means that the technical basis of the tool is suitable to simulate the achievable CO_2 emissions of concepts that reduce driving resistance. Therefore, maximum achievable impacts on air drag and mass can be taken into account quite easily. The key points are summarised in Table 1. Some innovations may not be utilised all of the time, e.g. the TRANSFORMERS lowerable roof may only be lowered if cargo allows. Similarly the double deck feature is only beneficial when more cargo can be stowed than would have been in a baseline situation with a conventional trailer. This means that to determine the average CO_2 emission, a utilisation rate needs to be taken into account. Hybridisation may be harder to integrate. Different approaches are possible with complexity increasing as more accuracy is required, Tansini et. al. (2017).

Table 1 Changes needed to VECTO

TRANSFORMERS innovation	Is the measure covered by the VECTO certification proposal?	What needs to be adapted
Aerodynamic Improvements	No; only standard bodywork and trailers allowed	The constant speed test can be used to determine Cd*A of the vehicle with innovative trailer concept. Alternatively, a certified calculation method can be used to determine Cd values. Requires a utilisation rate when the measure is not 100% active.
Loading Efficiency	No, only fixed payload and cargo volume	Requires allowance of a different payload input and a utilisation rate when the measure is not 100% active.
HoD	No	Requires development of a hybrid VECTO add-on. Complexity and development time can be significant, depending on required modelling accuracy.
Weight	No, only standard bodywork and trailers	Add an input field for alternative mass of the trailer.

11. Conclusions

By looking at the tractor/ semi-trailer combination holistically to reduce overall fuel consumption while in parallel improving load efficiency, TRANSFORMERS targeted, and achieved, a 25% energy consumption reduction per tonne.kilometre of goods transported in real world scenarios within the existing European regulatory framework. This reduction was achieved without significant effect on the road infrastructure. The TRANSFORMERS partners have worked together to develop and successfully demonstrate across Europe two highly innovative semi-trailer combinations, see Fig. 8.

Fig. 8 The TRANSFORMERS Combinations on the Public Road in Sweden

TRANSFORMERS developed ways of improving overall transport efficiency for both weight and volume limited assignments:

- For volume limited assignments TRANSFORMERS explores increasing the load capacity within current weights and dimensions regulations.
- Reduced fuel consumption can be achieved by improved aerodynamics. TRANSFORMERS looks at transport assignments which are weight limited, or for other reasons do not utilise the full trailer volume. If the full volume is not needed for the payload, TRANSFORMERS has the possibility to change the shape of the trailer to improve the aerodynamic characteristics of the full vehicle.

The TRANSFORMERS goals were achieved through the following innovations:

- A semi-trailer mounted “Hybrid-on-Demand” (HoD) electric driveline was developed, including a pre-standardisation tractor-trailer communication framework to enable widespread market introduction and provide planning certainty for future research activities.
- Mission-based, transformable whole vehicle aerodynamics.
- An internal trailer design offering increased load capacity.
- TRANSFORMERS explores the potential benefits of these innovations in the context of offering a mission adaptable solution so that the complete vehicle can be reconfigured and optimized for each assignment, rather than accepting a one size fits all solution.

In general, it can be concluded that the TRANSFORMERS project was very successful. All innovations have demonstrated saving potentials when assessed against the project goals depending on the mission profile. Additionally, all innovations have shown the potential for a viable business case in the future, and offer further improvement potential.

The TRANSFORMERS innovations require further development before market introduction is possible, with the following improvements feasible based on the simulation work:

- Weight reduction of HoD system and aerodynamic measures may result in an additional 0.5 to 1% saving.
- An optimised HoD control strategy was found to offer additional benefits of approx. 1-3%. A dynamic strategy based on predictive energy management could show even more potential.
- Adding plug-in functionality will bring benefits in certain mission profiles with limited regeneration potential.

The concepts will be developed further in the AEROFLEX project as a stepping stone to commercialisation.

The nature of the TRANSFORMERS approach is to consider the tractor-trailer combination as a complete vehicle, which can be reconfigured at the time of use. Being able to optimally select the correct measures depending on the loading condition and mission, allows the end user to fully exploit the fuel saving potential without needing to rely on a predefined fixed configuration. As a result of the mission adaptable approach, the optimisation potential can be combined.

Considering a tractor and trailer holistically can reduce the energy used to transport goods significantly, but needs cooperation between all players in the road transport industry. What further steps are needed?

- Continued cooperation between industry players is necessary to:
  - Further optimise the concepts and their reliability
  - Apply concepts to other vehicle combinations
  - Field test in real life conditions with shippers and carriers
  - Test interaction with other concepts such as platooning, alternative fuels, and high capacity vehicles.
  - Optimise communication between the tractor and semi-trailer (configurable roof, HoD, load capacity monitoring)
  - Fine-tune the business case to create markets of scale
- Enable the concepts within the EU and national legal frameworks, and international standards
- Incentivise the concepts
- Increased visibility of project results to underpin technical, market, and policy discussions.

Acknowledgements

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 605170.

References

European Parliament and European Council, 2015, Directive (EU) 2015/719 amending Council Directive 96/53/EC http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32015L0719&from=EN

Bouteldja, M., Ieng, S.-S., Schmidt, F., Schwieger, K., Saleh, P., Compliance of vehicle configurations with infrastructure geometrical constraints, in quasi-static and in dynamics, TRANSFORMERS Deliverable 5.4 (public).

Gonzalez, A., Schmidt, F., 2017, Effect on bridges of the various vehicle configurations, TRANSFORMERS Deliverable 5.2 (public).

Hariram, A., Kyncl, J., Barbarino, S., 2014, Defining end user metrics for evaluating a hybrid heavy duty commercial vehicle, IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, China.

Hillbrand, B., Weiss, G. B., 2017, Report on comparison results of simulation and testing, TRANSFORMERS Deliverable 6.3 (public).

Hornych, P., Geffard, J.-L., Glaeser, K.-P., 2017, Study of mechanical impacts of vehicle configurations on pavements (stress-strain response, fatigue, rutting), TRANSFORMERS Deliverable 5.1 (public).

Jacob, B., Schmidt, F., Billiet, M., 2017, Recommendations for EC wide regulatory framework (legislation) on dimensions and loads of vehicles, TRANSFORMERS Deliverable 5.5 (public).

Meurer, B., Klement, R., Queckenstedt, B., Harder, J., Mederer, M., 2015, E-mobility entering semitrailers – new requirements and impact on future semitrailer brakes, XXXIV International µ-Symposium Brake Conference, Bad Neuenahr.

Nitzsche, G., Wagner, S., Engel, M., 2017, Electric Drivelines in Semitrailers – TRANSFORMERS: An additional Way to Hybridisation, VDI Commercial Vehicles Conference, Friedrichshafen.

Nitzsche, G., Wagner, S., Baert, R., Engels, F., Maillet, C., 2018, TRANSFORMERS - Test Drive Results of a new Hybridisation Concept for Truck-Semitrailer Combinations, Proceedings of 7th Transport Research Arena TRA 2018, Vienna.

Schwedhelm, H., Yu, X., 2018, Impact of heavy goods vehicles with different payload on crashworthiness of safety barriers, Proceedings of 7th Transport Research Arena TRA 2018, Vienna.

Tansini, A., Grigoratos, T., De Gennaro, M., 2017, Proposal on the enhancement of CO2-declaration methods to support Hybrid Commercial Vehicles. ECOCHAMPS Deliverable 1.4 (public).

Van Zyl, S., Wilkins, S., Hommen, G., Van Eijk, E., Balau, A., Baert, R., Hillbrand, B., Jonkers, F., Maillet, C., Bertens, T., 2017, Final Report and Conclusion, TRANSFORMERS Deliverable 6.4 (public).

Van Zyl, S., Veerle, H., Ligterink, N., 2017, Using a simplified Willans Line approach as a means to evaluate the savings potential of CO_2 reduction measures in heavy-duty transport, Journal of Earth Sciences and Geotechnical Engineering, vol. 7, no. 1, pp. 99-117