Executive summary

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 within the road haulage industry. The project combines these innovations in semi-trailer combinations that are easily adaptable so that they can be optimised for each transport mission. TRANSFORMERS is a 13 partner European research project, which has received funding under the EU Seventh Framework Programme under Grant Agreement No. 605170.

The overall objective of the TRANSFORMERS project is to develop and demonstrate innovative, energy efficient and load optimised semi-trailer combinations for 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 tonnes*kilometres of goods transported in real world scenarios within the existing European regulatory framework. This reduction is targeted without affecting the road infrastructure. This is achieved through the following innovations:

- 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.

The targets for the innovations are illustrated in the figure below.

The work structure of the project is illustrated in the figure below.
The impact on the highway infrastructure is outside the scope of this deliverable, and is reported separately in Deliverable 5.5 “Recommendations for EC wide regulatory framework (legislation) on dimensions and loads of vehicles”. In summary the TRANSFORMERS innovations were not found to have a significantly different impact on the transport infrastructure to conventional vehicles. An overall look at the goals and achievements of TRANSFORMERS will be available in the final Publishable Report, which will be complementary to this deliverable and D5.5.

This deliverable, D6.4 “Final report and conclusion”, focusses on the outcome of the evaluation activities derived from testing and simulation results. It addresses the achievements of the project in terms of the overall project goals, namely a 25% energy consumption reduction per tonnes*kilometres of goods transported and selected Key Performance Indicators (KPI’s) defined in the early stages of the project. The deliverable focuses on the KPI’s related to the impact of the innovations in terms of energy consumption, fuel consumption and CO₂ emission, since these are reflected in the overall goal of the project. 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.

END USER REQUIREMENTS

Chapter 2 provides an overview of the road transport industry in Europe, end user requirements giving the rationale behind the TRANSFORMERS innovations, Key Performance Indicators (KPIs), and the evaluation scenarios. The TRANSFORMERS vehicles and innovations are introduced, as well as the evaluation framework used to assess the innovations.

Successful market acceptance of the TRANSFORMERS innovations can be evaluated by comparing the performance against existing state-of-the-art tractor/semi-trailer combinations. In addition to an Advisory Board, the project established a broad End User Group which allowed ‘End User’ KPIs to be established for different key performance areas. 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, see figure below.

TRANSFORMERS DEMONSTRATION VEHICLES

TRANSFORMERS developed and demonstrated 2 tractor/ semi-trailer combinations:
- Energy Efficiency or “Hybrid-on-Demand” (HoD) combination
- Load Optimisation combination

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:
- A semi-trailer mounted, distributed "HoD" 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.
- 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 curved front bulk head, side skirts, boat tail, and a single segment lowerable roof. The roof can be moved into 4 alternative positions, two of which are shown in the figure below, with the roof deflector on the tractor adjusted to suit.

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 a wide variety of shapes (two of which are seen in the figure below).

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 the figure below. The evaluation steps include real world testing, high fidelity simulations, evaluation of the results, and assessment of the economic potential.
Based on vehicle test measurements and high fidelity simulation results, a consolidated model has been used for the final evaluation which is reported in this deliverable. The improvement potential of the TRANSFORMERS innovations for selected transport missions has been compared to current heavy-duty vehicle technology used for similar assignments.

The figure below shows the trade-off between the various assessment methods used to evaluate the project in terms of fidelity and number of missions assessed. The evaluation model makes use of both the test results and high fidelity simulation results, in order to evaluate the effectiveness of the TRANSFORMERS innovations under various influencing parameters such as road type, payload and traffic conditions.

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. The scenarios used for the evaluation were agreed with IRU and included:

- 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)

The routes were then matched with routes for which data including HGV speed profiles were available. Chapter 2 explains the route selection in more detail.
TEST RESULTS

Chapter 3 summarises the results from the testing undertaken by TRANSFORMERS. The demonstrators have been extensively tested both on the test track and on the road.

The following tests are considered in this deliverable:
- Test driver responses on vehicle dynamics
- Impact on loading efficiency
- Impact of the aerodynamic measures
- Impact of the HoD system in real world conditions on public highways, and in simulated urban heavy traffic conditions
- The use of load volume sensors was demonstrated

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
- Functional safety and functionality tests developed together with TÜV Rheinland
- Commissioning tests
- 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

These steps and their outcome are briefly described in this deliverable. The results showed the dynamic behaviour is close 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 tractor/semi-trailer combination. Under some conditions the torque supplied from the HoD driveline could felt to be unstable, revealing that the control software requires further optimisation.

**Loading Efficiency**

Loading efficiency tests on the Load Optimisation Trailer are described which investigate the effect of the configurable roof, increased inner floor length and double floor system in terms of the 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 more typical 33. The 4 segment configurable roof was found to take approximately 1 minute to change to a new configuration. The “flex floor” system was tested successfully and the time to load/unload 4 pallets was 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.

**Aerodynamics**

Only the aerodynamic features of the Energy Efficiency Trailer were tested, using both the DAF and Volvo tractors. The aerodynamic measures of the Load Optimisation Trailer were not part of the test program with regards to fuel consumption, however, they were functionally tested.

The aerodynamic tests were all undertaken on test tracks with the aerodynamic measures in relevant settings, such as boat tail folded in or out, and with various roof configurations. The Volvo tests focussed on measuring the fuel consumption benefit of the aerodynamic measures at various constant speeds increasing from 60 km/h (aerodynamic measures are not effective at low speeds). 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 the 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 on fuel consumption in the evaluation phase.

**Hybrid-on-Demand Fuel Savings**

The Energy Efficiency Trailer HoD system 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. 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.

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.

**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 management (e.g. use different battery models without changing the holistic model), 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.

After the models were validated against the test results, the aim of the simulations described in Chapter 4 was to determine an optimal configuration to maximise fuel savings potential. To achieve this goal, key system parameters were varied. This resulted in a high number of variations that were represented in a “simulation matrix”. Configuration variations were agreed within the consortium, and were simulated for the different route scenarios to identify the most promising. 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. Results are discussed.

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.

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. More investigation of the optimum system strategy for different routes is needed.

The plug-in scenario does not show improvements for all cases simulated, but offers up to 4% higher fuel savings for some routes. More investigation of the optimum system strategy for plug-in systems is needed for different routes is needed.

In summary there is still a high potential for improvements using different control strategies for different route scenarios. 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, depending on the type of route. Predictive energy management systems could take actual road and traffic conditions into account and would be able to optimize fuel savings.
EVALUATION

The test measurement results (Ch.3) show the potential of single TRANSFORMERS innovations for a limited number of configurations and test routes. The simulation results (Ch.4) investigated the effectiveness of the HoD under different route conditions, and for variations in the configuration of the system. Chapter 5 analyses these results in more detail in order 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. Chapter 5 focuses on the evaluation of 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 CO₂ is equivalent to the impact on fuel consumption, the latter is used as the primary metric in Chapter 5. The key inputs to the evaluation are described, the saving potential of the individual and combined TRANSFORMERS innovations are discussed, along with future potential.

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 describe the relation between the power demand at the wheels and the fuel rate of the engine. 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 results against the original goals of the project in terms of energy use reduction, the following can be 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%. See figure below.

- 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 in 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.

ECONOMIC ASSESSMENT

In Chapter 6 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 available within the project for confidentiality reasons, the assessment is limited to the economic saving potential based on the impact on fuel consumption from the previous chapter. The evaluation has been done for the three different innovations separately, as well as when combined. The use cases, assumptions, assessment approach and results are provided.

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 reasonable 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 in the future for all innovations. Details are provided.

The best cases for the different innovations differ. The best use case for the combined TRANSFORMER 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) 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 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.

ROAD TOWARDS IMPLEMENTATION

Chapter 7 explores the road towards the commercialisation of the innovations, discussing recommendations for technical improvements and paths towards exploitation. The TRANSFORMERS innovations that have been developed and demonstrated need further development to enable commercialisation, including:

- Demonstration of acceptable durability in different conditions, i.e. field testing
- Optimisation of components, and especially of the HoD system
- Reducing the complexity of the solutions
- Reducing the 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 per unit costs.

Chapter 7 ends with an extensive discussion of the compatibility of the TRANSFORMERS innovation characteristics with the VECTO tool, which is to be used in the near future for the assessment of the CO₂ impact of heavy-duty vehicles in certification procedures. The current VECTO proposal does not allow the CO₂ reduction measures of the TRANSFORMERS concept to be taken into account, because currently only the simulation of vehicles with non-hybrid powertrains and standard truck/semi-trailer bodywork is included. The VECTO tool itself, however, is designed to simulate CO₂ 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 CO₂ emissions of innovative concepts that reduce driving resistance. Therefore, maximum achievable impacts of air drag and mass can be taken into account quite easily. The key points are summarised in the table below.
### TRANSFORMERS innovation

<table>
<thead>
<tr>
<th>Is the measure covered by the VECTO certification proposal?</th>
<th>What needs to be adapted?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic improvements</td>
<td>No, only standard bodywork and trailers allowed</td>
</tr>
<tr>
<td>Loading efficiency</td>
<td>No, only fixed payload and cargo volume</td>
</tr>
<tr>
<td>HoD</td>
<td>No</td>
</tr>
<tr>
<td>Weight</td>
<td>No, only standard bodywork and trailers</td>
</tr>
</tbody>
</table>

Some innovations may not be utilised all of the time. The TRANSFORMERS lowerable roof may only be lowered if cargo allows it. 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 CO₂ emission a utilisation rate needs to be taken into account. Hybridisation may be harder to integrate. In theory different approaches are possible with complexity increasing as more accuracy is required.

### 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 tonnes*kilometres of goods transported in real world scenarios within the existing European regulatory framework. This reduction was achieved without significant effect on the road infrastructure.

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 also be achieved by improved aerodynamics. In this respect TRANSFORMERS 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 the payload, TRANSFORMERS investigates 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, distributed “Hybrid-on-Demand” (HoD) electric driveline, including a pre-standardisation tractor-trailer communication framework to enable market introduction and provide planning certainty for future research activities. 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 to the optimum configuration for each assignment, rather than accepting a one size fits all solution.

The TRANSFORMERS partners have worked together to develop and successfully demonstrate two highly innovative semi-trailer combinations, see figure below.
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 highest potential for a positive business case is offered by the load optimisation measures, followed by the aerodynamic measures and the Hybrid-on-Demand.

The TRANSFORMERS innovations require further development before market introduction is possible, and the following improvements are believed to be feasible based on the simulation work:

- Weight reduction for the HoD system and aerodynamic measures may result in an additional 0.5 to 1% benefit in energy use reduction.
- Optimising the Hybrid-on-demand control strategy may result in additional benefits of approx. 3%. Further development and a more a dynamic strategy based on predictive energy management could show even more potential.
- Adding plug-in functionality to the HoD system will bring additional benefits in certain mission profiles with limited regeneration potential.

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 reconfigurable approach, the TRANSFORMER approach is able to combine the optimisation potential, rather than the average fuel saving potential.

Within the context of the current and future market, recommendations are made towards the implementation of TRANSFORMERS results. 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 interesting concepts such as platooning, use of alternative fuels, high capacity vehicles.
  - Optimise communication between the tractor and semi-trailer (configurable roof, HoD, load capacity monitoring)
  - Fine-tune the business case - try to create markets of scale
- Enable the concepts within the EU and national legal frameworks, and international standards
- Incentivise the concepts
  - Legislative incentives
  - Non-legislative incentives
- Increased visibility of project results to underpin technical, market, and policy discussions.
Contents

1 Introduction .......................................................................................................................16
  1.1 Project objective and key innovations .................................................................16
  1.2 Aim of this report .....................................................................................................16
  1.3 Approach ....................................................................................................................16
  1.4 Structure of the report ..............................................................................................17

2 Road transport industry and user requirements .............................................................18
  2.1 Road freight statistics ..............................................................................................18
  2.2 User requirements .....................................................................................................22
  2.3 Key Performance Indicators .....................................................................................24
    2.3.1 Assessment of the vehicle dynamics ...............................................................25
    2.3.2 Assessment of loading efficiency .................................................................25
    2.3.3 Aerodynamic Assessment ..............................................................................26
    2.3.4 Assessment of the hybrid-on-demand (HoD) system ....................................26
  2.4 Route and scenario selection .....................................................................................27
  2.5 The TRANSFORMERS demonstrators ...................................................................29
  2.6 Evaluation Framework ..............................................................................................32

3 Test results using the TRANSFORMERS demonstrators ...............................................34
  3.1 Vehicle dynamics testing .........................................................................................34
  3.2 Test drivers opinion .................................................................................................35
  3.3 Loading efficiency tests ............................................................................................36
    3.3.1 Configurable roof .............................................................................................37
    3.3.2 Flexible floor .....................................................................................................37
  3.4 DAF tests with the Energy Efficiency Trailer ............................................................39
    3.4.1 Aerodynamics testing ......................................................................................39
    3.4.2 HoD system testing ..........................................................................................40
  3.5 Volvo tests with the Energy Efficiency trailer ............................................................42
    3.5.1 Aerodynamics testing ......................................................................................42
    3.5.2 HoD system testing ..........................................................................................43

4 High fidelity simulations on optimal HoD configuration ................................................47
  4.1 Aim and approach .....................................................................................................47
  4.2 Model description .....................................................................................................47
  4.3 Model input ...............................................................................................................49
    4.3.1 Vehicle parameters and hybrid configurations ...............................................49
    4.3.2 Route specifications ..........................................................................................49
  4.4 Model results for case 3 ............................................................................................52
    4.4.1 Model Results for S3 (frequent elevation changes) .........................................52
    4.4.2 Model Results for S4 (steep hills) ...................................................................53
    4.4.3 Model Results for S5 (urban) .........................................................................53
    4.4.4 Conclusion ........................................................................................................53
  4.5 Model results for case 4 and plug-in scenarios ..........................................................54
    4.5.1 Model Results for S3 (frequent elevation changes) .........................................54
5 Evaluation results ......................................................... 57
5.1 Aim and approach .................................................. 57
5.2 Model description and simulation inputs ....................... 57
  5.2.1 Hybrid efficiency .............................................. 57
  5.2.2 Aerodynamic efficiency ...................................... 58
  5.2.3 Loading efficiency ............................................ 59
5.3 Savings potential of TRANSFORMER innovations ............ 60
  5.3.1 Potential of the HoD system (C) ............................ 61
  5.3.2 Aerodynamic loss reduction due to advanced aerodynamics (B) ......................... 62
  5.3.3 Loading efficiency increase due to double load floor (A) ............................ 63
  5.3.4 Combined effects (A+B, A+C, B+C, A+B+C) .................. 64
5.4 Future potential of TRANSFORMER technologies ............ 64
5.5 Conclusions ....................................................... 64
6 Economic assessment of the TRANSFORMERS innovations 65
  6.1 Definition of the use cases ..................................... 65
    6.1.1 Short distance international transport .................... 65
    6.1.2 Long distance international transport ....................... 65
    6.1.3 Urban round trip .......................................... 66
  6.2 Assessment approach and assumptions ......................... 67
    6.2.1 Assessment approach ...................................... 67
    6.2.2 Assumed parameters ...................................... 67
    6.2.3 Technology scenarios ..................................... 68
  6.3 Assessment results ............................................ 68
    6.3.1 Results of individual measures .......................... 68
    6.3.2 Combinations of measures ................................ 71
  6.4 Conclusions .................................................... 72
7 Roads towards implementation ..................................... 73
  7.1 Recommendations for technical improvements .......... 73
    7.1.1 Aerodynamic improvements because of the configurable roof ................... 73
    7.1.2 Load optimization measures ................................ 74
    7.1.3 Hybrid on Demand powertrain ................................ 74
  7.2 Paths towards exploitation .................................... 74
  7.3 Project-execution specific lessons learned .................. 76
  7.4 Assessing the CO₂ impact using VECTO ...................... 77
    7.4.1 Aerodynamic measures .................................... 78
    7.4.2 Loading efficiency measures ................................ 78
    7.4.3 Hybrid on Demand (HoD) trailer .......................... 79
    7.4.4 Weight ..................................................... 79
    7.4.5 Conclusions ................................................ 79
8 Conclusions ........................................................ 81
9 References

10 Acknowledgment

Appendix List

Appendix A – Evaluation approach

Appendix B – Detailed evaluation results
**Definitions**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EMG</td>
<td>Electric Motor Generator</td>
</tr>
<tr>
<td>Gvw</td>
<td>Gross Vehicle Weight</td>
</tr>
<tr>
<td>HoD</td>
<td>Hybrid on Demand</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indictor</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Project objective and key innovations

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

TRANSFORMERS is a 13 partner European Research project, which has received funding from the European Union Seventh Framework Programme for research, technological development and demonstration under Grant Agreement No. 605170.

The overall objective of the TRANSFORMERS project is to develop and demonstrate innovative, energy efficiency and load optimised semi-trailer combinations for long haul transport missions. TRANSFORMERS combines a modular approach for mission rightsizing by means of distributed hybridisation, and semi-trailer designs that include innovations improving both the aerodynamics of the full vehicle combination and load capacity. By combining reduced energy consumption with increased load efficiency, TRANSFORMERS targets a 25% energy consumption reduction per tonne*kilometres of goods transported in real world scenarios within the existing European regulatory framework. This reduction is targeted without affecting the road infrastructure. This is achieved through the following innovations:

- A semi-trailer mounted “Hybrid-on-Demand” (HoD) electric driveline, including a prestandardisation tractor-trailer communication framework to enable widespread market introduction and provide planning certainty for future research activities.
- Mission-based, transformable vehicle aerodynamics of the combination.
- An internal trailer design offering increased load capacity.
- Mission adaptability to allow optimisation of the vehicle combination for each load or transport mission.

1.2 Aim of this report

This final report of the TRANSFORMERS project addresses the achievements of the project against the overall goal and key-performance-indicators (KPI’s) defined in the early stages of the project. The report will focus on the KPI’s related to the impact of the innovations in terms of energy consumption, fuel consumption and CO2 emission, since these are reflected in the overall goal of the project. Based on this, the economic potential of the innovations will be addressed in a wide array of transport applications, as a basis for detailed future business case analyses. This assessment of the innovation impact is the basis for a discussion of the future potential of the innovations, implementation strategies and next steps.

The impact on the highway infrastructure is outside the scope of this deliverable, and is reported separately in Deliverable 5.5 “Recommendations for EC wide regulatory framework (legislation) on dimensions and loads of vehicles”. In summary the TRANSFORMERS innovations were not found to have a significantly different impact on the transport infrastructure to conventional vehicles. An overall look at the goals and achievements of TRANSFORMERS will be available in the final Publishable Report, which will be complementary to this deliverable and D5.5.

1.3 Approach

The impact assessment of the TRANSFORMERS innovations is based on the test campaigns using the TRANSFORMERS demonstrator vehicles. Since the test results cover only a very limited portion of the possible applications of the TRANSFORMERS innovations, models are used to assess the benefit of the innovations in a wide array of application areas. This report will not only show the results, but also the modelling approaches including their benefits and limitations.
The input for this report is based on other deliverables in the TRANSFORMERS project. Where appropriate, these deliverables will be referred to and where required summaries of these deliverables will be used, e.g. in case deliverables are not public.

1.4 Structure of the report

This final TRANSFORMERS report takes off with an overview of the road transport industry and user requirements in chapter 2, leading to the rationale behind the innovations developed and demonstrated in the project. Furthermore, the demonstrator trailers and their key innovations will be introduced, as well as the evaluation framework required to assess the impact of the innovations in real world conditions and the transport route characteristics used for these calculations.

In chapter 3 the test results of the TRANSFORMERS demonstrator trailers and vehicles are discussed, which are a basis for the adjacent simulations and evaluation. The key tests done in the project show a wide variety in their approach, following the characteristics of the TRANSFORMERS innovations. After briefly summarizing the vehicle dynamics tests and test drivers opinion, the results of the loading efficiency tests, aerodynamic measures and Hybrid-on-Demand system in various circumstances will be discussed.

The test results are input for the simulations to derive the optimal Hybrid-on-demand configuration. In chapter 4 the approach and key inputs are introduced, followed by the simulation results for the most important transport routes, which will also be used for the evaluation.

Both the test results and simulation results feed into the evaluation framework, which is used for the impact assessment of the TRANSFORMERS innovations in a wide range of transport applications. In chapter 5 the approach and key inputs for this evaluation will be introduced, leading to an assessment of the savings potential of the single innovations. Combining the effect of the TRANSFORMERS innovations will reveal if the overall project goal is reached or not, followed by brief view of the future potential of the innovations.

The calculations of the energy consumption and fuel saving potential of the TRANSFORMERS innovations are the basis for the economic assessment in chapter 6, in which the economic savings in several realistic mixed environment transport applications will be discussed. These economic savings are the basis for future detailed business case calculations in possible follow up projects.

The developed and demonstrated TRANSFORMERS innovations have shown their benefit in real world applications, however, they are not yet ready for large scale production. Chapter 7 explores the required roads towards the implementation of the innovations, discussing recommendations for technical improvements and paths towards exploitation. This chapter also includes project specific lessons learned and ends with an extensive discussion of the compatibility of the innovation characteristics with the VECTO tool, to be used in the near future for the assessment of the CO₂ impact of heavy-duty vehicles in certification procedures.

This final TRANSFORMERS report closes with the key conclusions resulting from the project and a look into the future.
2 Road transport industry and user requirements

This chapter provides an overview of the Road Freight Industry in Europe and end User Requirements described in Deliverable 1.1, the Key Performance Indicators (KPIs) identified in Deliverable 1.2 and the identified test cases and scenarios described in Deliverable 1.3.

2.1 Road freight statistics

Raw materials and finished goods can be transported from the manufacturing site to the distribution centre and onwards to the end consumer by air, rail, road or water-based transport services. However, the transport of goods by road accounts for 75% of the tonne-kilometres of freight transported within the European Union [1]. Road transport is particularly dominant in the distribution of finished products at the lower level of the supply chain, particularly in the delivery of retail supplies.

In Deliverable 1.1 of TRANSFORMERS project, the road freight transport industry was assessed, with respect to the interaction of a truck-trailer configuration and the key stakeholders involved. Its purpose was to provide a tool for identifying relative areas of strength and weakness and to prioritize opportunities for collaborative action to build scale for a new configurable and adaptable Hybrid-on-Demand Truck Trailer configuration.

The standard European semi-trailer combination has a Gross Combination Weight of 40 tonnes, and within the restrictions on vehicle dimensions, e.g. maximum combination length of 16.5m, limits the payload to approximately 26t or 85-90m$^3$ volume, which equates to an ideal commodity density of approximately 300kg/m$^3$. As can be seen in Figure 2.1, the number of commodities with the ideal density are relatively few. In the case of heavy materials such as liquids or construction materials, the transport is typically weight limited and the volume is underutilized. For lighter commodities such as white goods or mixed parcels, the transport is volume limited and the weight capacity is underutilised.

<table>
<thead>
<tr>
<th>EXAMPLE COMMODITIES</th>
<th>DENSITY (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAVY Construction materials</td>
<td>700-790</td>
</tr>
<tr>
<td>Liquids</td>
<td>600-1000</td>
</tr>
<tr>
<td>IDEAL Beer crates with empty bottles</td>
<td>300</td>
</tr>
<tr>
<td>LIGHT Parcel</td>
<td>150</td>
</tr>
<tr>
<td>White goods, e.g. refrigerators</td>
<td>130</td>
</tr>
<tr>
<td>Plastic foam</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 2.1 Density of transported goods

An overview of the primary components of different vehicle combinations available on the market can be seen in Figure 2.2:
Comparison of distance classes, shipment types and goods shipped, along with the inherent structure of the long distance road freight transport sector yield some interesting observations:

- In 2008, about 6.5 million heavy goods vehicles above 3.5 tonnes were registered in the European Union. On average 72% of road freight transport in the EU is carried out with articulated vehicles consisting of a tractor and semi-trailer. 87.4% of the semi-trailers used have a payload capacity of more than 20 tonnes. The articulated vehicle consisting of a two-axle tractor and three-axle semi-trailer with one axle which can be lifted is estimated to be the most common vehicle combination used intra-EU freight transport. The average empty weight of such a combination running on diesel is 14 tonnes. Considering a maximum authorized weight of 40 tonnes, such a vehicle combination can carry a maximum payload of 26 tonnes or between 85 and 90 m$^3$ of volume.

- In tonnes, two of the dominant groups relate to materials for the construction industry (sand gravel and cement) and agricultural products. Food, beverages and tobacco and the products of agriculture are the second largest element with secondary raw materials, including municipal wastes, another important group. In terms of tonne*kilometres, the most important product groups are food, beverages and tobacco and agricultural products (27% of the total together), both groups being carried for relatively long distances and feeding into the food supply chain. Construction related materials, including wood products, form a second group and make up a combined 26% of the total. These are followed by chemicals (8%) and metal products (7%). One final important category is grouped goods carried together, mainly palletized transport, (8%), an important group to ensure full use is made of road freight capacity.

- 41% of the goods shipped over all distances are palletized (Figure 2.3)

- 56% of the goods transported in tonne*kilometres are greater than 300 kilometres (Figure 2.4)
62% of all goods transported in tonne*kilometres and 64% of all goods transported in tonnes are dry bulk goods and palletized goods (Figure 2.5)

Improved safety and reliability results in fewer days lost due to injury, fewer vehicles off the road for repair, fewer missed orders, less need for investigation and follow up.

Fuel price accounts for more than 30% in the Total Cost of Ownership (Figure 2.6), thus reducing fuel consumption provides a two pronged approach that can improve both the profitability and the environment.
Thus, looking across a high level summary of the road freight transport sector in Europe, it is clear that transport volumes will continue to grow with economic growth; and the problem to accommodate freight flows in an efficient and sustainable way becomes increasingly alarming. The uptake of EURO norms linked with the taxation at tolls have definitely contributed towards the reduction of emissions in Road Freight Sector, however with an increasing momentum around issues such as climate change, resource scarcity, sustainability and pollution it brings to light critical challenges that the transport by road will face in the coming years. For companies, the greening of logistics not only has an environmental and social dimension, but is also a question of economics and efficiency.

Based on the data presented above, TRANSFORMERS project chooses to focus on palletised goods for regional and long haul transport, as showed in Figure 2.7:

TRANSFORMERS improves overall transport efficiency in two ways by looking at the weight and volume limited assignments separately. For volume limited assignments TRANSFORMERS explores increasing the load capacity within current weights and dimensions regulations.

Reduced fuel consumption can also be achieved by improved aerodynamics. In this respect TRANSFORMERS looks at the complete vehicle, but in relation to transport assignments which are weight limited, or for other reasons do not operate at maximum volume. If the full volume is not needed why pull a partly empty 4m high vehicle through the air, and instead TRANSFORMERS investigates the possibility to change the shape of the vehicle to improve aerodynamic characteristics of the full vehicle.
TRANSFORMERS also explores the potential benefits of these innovations in the context of offering a mission adaptable solution so that the complete vehicle can be reconfigured to the optimum configuration for each assignment.

2.2 User requirements

The analysis reported in Deliverable 1.1, and shortly in this document, is partly based on the experience of Procter & Gamble’s operations in Europe, the International Road Transport Union (IRU) and the TRANSFORMERS End User Group. Using the information collected from these sources, it was possible to extrapolate the end user needs and requirements qualitatively. Information from the End-User Group was collected by organizing a preliminary workshop with the end user group, at Procter & Gamble and another workshop a month later at the International Road Transport Union. Figure 2.8 represents the stakeholders who were invited for the workshop or have been contacted by telephone for interview, or were contacted online to answer a questionnaire.

Figure 2.8 End User Group

Primary data for evaluating the truck use were collected from reports and statistics published by the European Union and other non-governmental and inter-governmental organizations, journal articles and book chapters that describe the road freight supply chains and trucking industry, by telephone interviews with logistics and supply chain managers. The wider assumptions were then discussed in a ‘brainstorming session’ by logistics specialists (academics, consultants and people who hold senior management positions within the end-users group). These discussions focused on the 4 pillars identified for end-user requirement and needs (), and was done in the second workshop.

As a result of time and resource constraints, the research was limited in several respects. First, telephone interviews were held with only five managers in each of the key sectors. To get a more representative view, larger, randomized samples of interviews would be required, preferably on a face-to-face basis. Second, heavy reliance was placed on expert judgment. If sufficient operational data could be obtained, managers’ qualitative assessments could supplement with quantitative modelling of the end user requirement and needs. Third, a broad set of road freight logistics data classified according to NST 2007 are available at Eurostats, with detailed data in terms of tonnes and tonne*kilometres until 2007 in micro level were identified, at the same time macro level data from 2009 – 2011 for the corresponding data were identified. For other sectors, it was necessary to extrapolate from the experience of individual firms and/or elicit the views of trade associations.

Since the industry in itself is huge and multiple stakeholders are involved in various stages, we have carried out this study by means of literature surveys, workshops with the stakeholders and survey by means of questionnaire to obtain inputs for defining and tuning the test case scenarios for the future truck and trailer configuration and definition of the assessment criteria for the forthcoming work packages. The following paragraphs explain the methodology adopted to identify the end-user requirements and needs in the next chapter.
The major performance evaluation areas are a broad set of parameters that the end users (shippers) consider are important for evaluating their transportation options and the transport service provider considers important for the success of their business in order to provide superior and reliable service to their clients. As explained earlier the demand for transportation is a secondary demand i.e. it’s requirement arises primarily from the end customer and the producer must evaluate dimensions like loading and shipping time, cost, capacity, reliability etc. to ensure that his end-customer is completely satisfied. From the standpoint of TRANSFORMERS measurement of some of these parameters may not lie within the scope of the project, but developing a solution that enable road freight service providers to improve transport capacity for shippers at competitive cost and a lower impact on the environment could lead to better acceptance of the solution proposed. Having conducted extensive literature surveys and numerous interviews with various key stakeholders it was understood clearly that the total additional cost incurred for the new truck-(semi)trailer must prove to be lower than the sum of the potential added values primarily in terms of fuel economy, maintenance costs and emissions and these data must be measurable and comparable with the existing truck-(semi)trailer combination with a maximum return on investment or pay out time of 30-36 months.

The proposed solution should be able to deliver on the key pillars mentioned below:
- Environmental: Reduction in greenhouse gas emissions, noise nuisance, other local pollutants, energy usage etc.
- Financial: Pricing and affordability, operational efficiency demonstrated by compliance with or exceeding key performance indicators etc.
- Social: accessibility in services, networks, rolling stock, infrastructure, capacity to adapt to demographic changes etc.
- Logistics: Loading and unloading time, transport capacity, capacity utilization etc.

![Logistic Provider/manager](image1)
- Better/Higher Fuel Efficiency
- Lower maintenance costs
- Superior vehicle uptime
- Cheaper Upgrades

![Service & Maintenance](image2)
- Easier access to engine/motor.
- Diagnosis tool/infrastructure without much of capital expenditure
- Availability of spare parts
- Lower Technical Skills

![Truck Driver](image3)
- Reliability
- Ease of Operation
- Better pickup and smooth operation
- Simple refuel/recharge operations

![End User](image4)
- Reliability
- Higher Capacity
- Lower Costs
- Faster commutation

![Regulators](image5)
- Infrastructure
- Environment and pollution levels
- Gridlock in Transportation
- Industry competitiveness

Figure 2.9 Highlights on the needs and requirements of the end users

Highlights on the needs and requirements of the end users are presented in Figure 2.9, and these aspects have been further elaborated in Deliverable 1.1.
2.3 Key Performance Indicators

In order to understand the needs, requirements, and the day to day challenges of the road transport industry, the project team engaged with all sides of the industry. This was achieved in part through the diverse range of project partners, but in particular through the establishment of a broad End User Group which includes the vehicle industry, and transport service providers and transport buyers. This provided a good understanding of the different perspectives of the various actors, taking into account their role in the industry and scale of their operations. The interaction also allowed appropriate Key Productivity Indicators (KPI) to be identified. The model used to identify KPIs is illustrated in Figure 2.10.

![Figure 2.10 KPI Identification Model](image)

Keeping the identification model in mind; the 'End User' KPIs were identified. They are different since they do not dive into evaluating the articulated vehicle combination from a purely technical standpoint, but rather they are based on evaluating the vehicle on parameters that affect and matter to business which operate and use these vehicles. Figure 2.11 shows the KPI Area’s identified. By comparing the performance of the new truck-(semi)trailer configuration, against the existing state-of-the-art truck-(semi)trailer configuration would be constructive for the successful market acceptance of the proposed alternative.

![Figure 2.11 Key Performance Area](image)

The identified end user key performance areas have been shown in the Figure 2.11, these performance indicators have been split horizontally into two sections according to the main beneficiary from the transport value chain for whom the performance parameter matters and vertically into six pillars as per the functionality.
It was evident that some of the parameters were qualitative and some difficult to measure within the scope of TRANSFORMERS due to paucity of time and technological maturity. Therefore it was decided to split the KPIs into those which will be measured during the project (more concrete measurements formulas provided in tables below). Those which belong to a “Soft” section are mentioned as relevant to end users in general, but will not be tested nor measured during the project lifespan and as such will only be explained briefly in the tables.

Future configurable and adaptable truck-(semi)trailers combinations need to be a viable alternative to existing combinations that are on the market today. The new combinations need to be attractive and efficient from an environmental, energy, operational and a logistics point of view. Furthermore, they must comply with the needs and expectations of logistics providers and end users, with the regulations and be able to operate on the existing road and multimodal infrastructure network. The above-mentioned KPIs serve as a basis for further development of works leading to the creation of a TRANSFORMERS truck.

Summarizing, it is important to ensure that there will be no loss of load capacity in terms of weight or volume as compared to a current average standard articulated combination, i.e. a compensation for the tonne lost to batteries needs to be found. It must be designed such that there are reduced complications during loading and unloading operations. Moreover, the reduction of 25% of fuel consumption compared to the average standard articulated vehicle is feasible (typical fuel consumption when empty is 22l/100km, and when full 28 l/100km). Lastly, the operational costs of the vehicle should not be higher than an average standard articulated combination.

The evaluation makes use of clear definitions of Key Performance Indicators (KPIs) which were defined in WP1 and reported in D1.2. These definitions were further elaborated on in WP6 for the test phase and resulted in a test plan as reported in D6.5.

In the following, a definition of the KPI’s used further in the evaluation will be presented.

### 2.3.1 Assessment of the vehicle dynamics

Part of the vehicle test program consisted of a combination of manoeuvrability tests and braking tests. The goal of these tests was to characterize the capacity of the vehicle to undergo specific manoeuvres in safe conditions, whatever the driving conditions.

No special KPI were identified in WP1 for vehicle dynamics. Since the vehicles would be subject to standardized test procedures, the requirement was that the behaviour of the TRANSFORMERS vehicle combinations would be within the requirements of these test procedures and similar to that of the reference (conventional) vehicle configurations.

### 2.3.2 Assessment of loading efficiency

In the loading/unloading tests, the effect of switching from a standard trailer to the Load Optimisation Trailer on a number of Key Performance Indices was measured. These KPI’s have been defined in Deliverable 1.2 of WP1 and are repeated here:

<table>
<thead>
<tr>
<th>KPI</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 1.3</td>
<td>Fill speed</td>
</tr>
<tr>
<td>KPI 1.4</td>
<td>Pay load capacity</td>
</tr>
<tr>
<td>KPI 1.5</td>
<td>Load Factor</td>
</tr>
<tr>
<td>KPI 1.6</td>
<td>Euro pallet / floor space</td>
</tr>
<tr>
<td>KPI 1.7</td>
<td>Inter-modality</td>
</tr>
<tr>
<td>KPI 4.1</td>
<td>compatibility for automated (un)loading</td>
</tr>
<tr>
<td>KPI 4.2</td>
<td>(un) loading performance</td>
</tr>
<tr>
<td>KPI 4.3</td>
<td>(un) loading safety</td>
</tr>
<tr>
<td>KPI 4.4</td>
<td>component safety</td>
</tr>
<tr>
<td>KPI 4.5</td>
<td>load securing</td>
</tr>
<tr>
<td>KPI 6.5</td>
<td>unloading/ docking ease</td>
</tr>
</tbody>
</table>

The work done and results obtained have been reported in detail in deliverable report D6.2 Only the main achievements (and corresponding KPI) will be handled in the following chapters.
2.3.3 Aerodynamic Assessment

Aerodynamic improvements for a complete vehicle (tractor-trailer) will result in fuel savings compared to a standard tractor-trailer combination. To measure the performance improvement reached in the Transformer project, the following two KPIs have been defined in WP1:

- **KPI1** - Vehicle drag force reduction:

\[
\Delta F_{\text{Drag}} = \frac{F_{D, \text{new}} - F_{D, \text{reference}}}{F_{D, \text{reference}}} \quad (2.1)
\]

with:
- \(F_D\) – Drag force
- \(\rho\) – Density of Air
- \(U_\infty\) – Speed of the vehicle relative to the surrounding
- \(\Psi_\infty\) – Yaw – angle of the surrounding air relative to the vehicle motion
- \(C_D(\Psi_\infty)\) – Drag coefficient as a function of yaw – angle
- \(A\) – Projected frontal area of the vehicle

- **KPI2** – Fuel consumption (FC) reduction achieved:

\[
\Delta \text{FC} = \frac{\text{FC}_{\text{new}} - \text{FC}_{\text{reference}}}{\text{FC}_{\text{reference}}} \quad (2.2)
\]

The drag force on a vehicle combination is defined as:

\[
F_D = \frac{1}{2} \rho U_\infty^2 C_D(\Psi_\infty) A
\]

KPI1 indicates the reduction in drag force due to aerodynamic improvements, it does not measure the impact of the increased trailer weight resulting from these improvements. KPI2 measures both effects.

2.3.4 Assessment of the hybrid-on-demand (HoD) system

Since the HoD trailer is a hybrid system, two corresponding Key Performance Indices have been identified:

- **KPI3** – The normalized consumed total energy:

\[
KPI3 = \frac{\text{Consumed Total energy}}{\text{tonne} \times \text{km}} \quad (2.3)
\]

Of course the primary source of energy is either fuel or electrical energy that has been charged to the vehicle and stored in the battery. In line with current conventions, the energy content present in fuel is determined from fuel mass consumption and from the lower calorific content of the fuel. The electrical energy that was consumed in that same trip is determined from the change in the amount of energy stored in the battery. It is common practice to estimate this energy content from the change in battery state of charge or SoC (assuming that the battery management system ensures that battery voltage changes are negligible). A 100 % reduction in SoC then corresponds to a nominal energy amount \(E_{\text{batt},\text{nom}}\). Of course to compensate for this reduction in state of charge a higher amount of electrical energy is to be charged from the grid. This is neglected in the above equation. When taking the SoC into account, the equation becomes:

\[
KPI3 = \frac{\Delta m_{\text{fuel}} H_u + \Delta SoC E_{\text{batt},\text{nom}}/100}{m_{\text{payLoad}} \times \text{L}\text{TRIP}} \quad (2.4)
\]

With:
- \(H_u\) [MJ/kg] – Fuel lower calorific value
- \(\Delta SoC\) [%] – State of charge change (positive when SoC is reduced)
- \(E_{\text{batt},\text{nom}}\) [MJ] – Battery pack capacity corresponding with 100 % SoC change

In the project, the SoC correction was needed only for the assessment of the HoD innovation. During the aerodynamic tests the HoD-functionality was not active. Furthermore it was agreed to account the SoC corrections in the following way (see Table 2.2 below based on typical industry figures):

| Table 2.2 Parameters used for SoC correction |

---

605170 – D.6.4 – Final Report and Conclusions 26 / 93
With Table 2.2 the calculation of KPI3 was modified to:

\[
\Delta m_{\text{SOC}} = 5.26 l \cdot \frac{\Delta \text{SOC}}{100} \cdot \rho
\]

\[
KPI3 = \frac{(\Delta m_{\text{fuel}} + \Delta m_{\text{SOC}}) \cdot H_u}{m_{\text{payload}} \cdot L_{\text{trip}}}
\]

- KPI4 – The share of recuperated energy in total energy consumed:

\[
KPI4 = \frac{\text{Consumed recuperated energy}}{\text{Consumed total energy}}
\]

Similarly as described above, the consumed recuperated energy can be calculated from cumulative energy that flowed from the battery towards the EMG during the trip. This then gives the following expression:

\[
KPI4 = \frac{E_{\text{batt}}}{\text{Consumed total energy}} \int_{\text{start}}^{\text{stop}} (\Delta \text{SOC}) \frac{dt}{dt}
\]

### 2.4 Route and scenario selection

In the second half of 2015 an investigation has been made with the goal to choose the best routes for evaluation of TRANSFORMERS results. As the project does not have possibility to perform large scale real-life testing, one of the main indications of benefits delivered by TRANSFORMERS solutions will be obtained from simulations.

The main process for choosing the routes has been consultation with members of the International Road Transport Union (IRU Projects is a partner of TRANSFORMERS), which are representatives of national hauliers from Europe and beyond. Part of this process has been presentation of the TRANSFORMERS project at the IRU CIT (Commission of IRU Members on Technical Affairs, 10th September, Boras, Sweden). Following this consultation, routes have been proposed to the TRANSFORMERS project members, and finally agreed at the consortium meeting in Paris on 27th October 2015.

The wide agreement amongst national representatives of road haulier companies is that there is no “typical” environment for delivery of goods by road in Europe, and that it is essential to investigate how project solutions can reduce fuel consumption in different environments. Therefore, the following driving “environments” have been selected:

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

In order to be able to use such environments in the planned simulations, specific routes had to be identified. A review of TEN-T corridors was performed to identify the specific stretches. TEN-T
Corridors are the main transport routes for goods by road in the EU. Furthermore, they are defined in close cooperation between the European Commission and Member States. These two reasons make them perfectly suitable as “blue-print” for TRANSFORMERS routes.

Following the selection of routes in D1.3 and D1.6 based on the input from haulier representatives, the expectation was, already from the definition stage, that some of them might change, because of simulation reasons (data availability in some cases might not be good enough e.g. traffic conditions or specific selected route). From road hauler representatives’ point of view, this is not a problem as long as the final routes used in the simulation have similar characteristics to the ones initially proposed.

The routes that were chosen in the end were indeed different, but the characteristics are close to the defined scenarios. An Energy calculation for every route has been done to make sure that the new routes can be compared to the previously defined routes.

The routes are presented in Table 2.3, in comparison with the initial routes proposed in WP1. In order to increase the number of simulations and to reduce the time required to perform them, a representative part of the long routes was selected for scenarios S2, S3 and S4. The respective distances of these shorter sections are shown in brackets.

<table>
<thead>
<tr>
<th>Route name</th>
<th>WP1 Intended Routes</th>
<th>WP2 Routes (real measurement data available)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Route</td>
<td>Distance [km]</td>
</tr>
<tr>
<td>S1 – flat</td>
<td>Bruges – Calais</td>
<td>114</td>
</tr>
<tr>
<td>S2 – mixed</td>
<td>Rotterdam – Warsaw</td>
<td>1227</td>
</tr>
<tr>
<td>S3 – hilly</td>
<td>Paris – Bordeaux</td>
<td>485</td>
</tr>
<tr>
<td>S4 – steep hills</td>
<td>Munich – Verona</td>
<td>340</td>
</tr>
<tr>
<td>S5 – urban</td>
<td>City of Brussels</td>
<td>6,56</td>
</tr>
</tbody>
</table>

On all these routes elevation changes and traffic conditions can severely impact the performance of the driving. Thus, in the simulations it is important to take into account not only the “free flowing” traffic but also high density traffic, during peak-hours.

Some of the important parameters that need to be considered in order to realize the potential of the solution can be seen in the table as shown in Table 2.4:

<table>
<thead>
<tr>
<th>Traffic Condition</th>
<th>Terrain Type</th>
<th>Road Conditions</th>
<th>Driving Cycles</th>
<th>Load Profile</th>
<th>Battery</th>
<th>Aerodynamic Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Flow</td>
<td>Flat</td>
<td>Wind</td>
<td>Aggressive</td>
<td>Fully Loaded</td>
<td>New/Old</td>
<td>Standard</td>
</tr>
<tr>
<td>Diversion</td>
<td>Hilly</td>
<td>Ideal</td>
<td>Normal</td>
<td>Partly Loaded</td>
<td>Hot/Cold</td>
<td>Roof Position</td>
</tr>
<tr>
<td>Congestion</td>
<td>Snow/Rain</td>
<td>Idling time</td>
<td></td>
<td>Empty</td>
<td></td>
<td>Front Deflector</td>
</tr>
</tbody>
</table>

Simulation results may vary heavily depending on the environment (including route) used for testing solutions. Thus it is essential to select the routes which represent relevant driving conditions. In Chapter 4 of this report, we will take a closer look at the initial routes proposed in WP1 and the routes used for simulations in WP2 and WP6, in order to prove that they are similar in respect to the total length, altitude profile, driving environment, traction and braking energy, and because of it, the selection criteria’s from WP1 still apply and WP2 routes and the shorter sections can be used in the analysis tool in WP6.
2.5 The TRANSFORMERS demonstrators

Two demonstrator trailers were designed and developed by Van Eck and Schmitz Cargobull in close cooperation with partners Bosch, Fraunhofer, TNO and third parties, 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 through the distributed electric driveline, known as Hybrid-on-Demand.

The key technologies of both demonstrator trailers are briefly introduced here. For more detailed information on the innovations and demonstrator trailer, see respective deliverables resulting from the TRANSFORMERS project.

**Load Optimization Trailer**

The Load Optimization trailer (Van Eck chassis, see figure 2.12) comprises innovations to carry additional goods and aerodynamic features.

- **An increased floor length** by optimizing the internal length of the trailer, to allow for the 34 pallets to be placed in the trailer. This 1 additional pallet compared to the baseline situation already creates an 3% benefit. The dock plate support is integrated in the trailer, so that the dock plate does not need to be shifted when loading the last pallets, saving operational time.
- **The flexible double floor** is made out of a galvanized steel frame with aluminium plates. It locks itself in every position with a ratchet so it can never drop down accidentally. It is pulled against end stops, who’s position can be preset, with a fork lift with long arms. The arms of the forklift fit in two levers that pop up out of the floor by hand. When the Flex Floor isn’t used, it forms the floor.
- **The aerodynamic features comprise side wings, boat tail and a 4-segment Configurable Roof.** The configurable roof is made out of a foam sandwich panel with aluminium side plates that cover the side walls. It moves stepless to all positions, a number of which can be preprogramed. 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 and not used in the evaluation. 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 electrically driven spindles. The movement is controlled by programmable logic controller In the front Bulkhead the interfaces for the flexible floor are also integrated.
Energy Efficiency Trailer
The energy efficiency trailer comprises aerodynamic features and a Hybrid-on-Demand system (Schmitz Cargobull chassis, see figure 2.13 below).

- 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 800 mm 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, for example, when the load is weight limited, or otherwise does not utilize the full volume. 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. In total 4 shapes are possible, from “high flat” up to “low tapered”, as shown in figure 2.14.

- The hybrid-on-demand (HoD) driveline consists of an electric motor and generator (EMG), a gearbox with an 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 existing trailer chassis design. 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. The HoD driveline is controlled from the trailer, taking a limited number fo additional signals from the tractor. For this a new tractor-trailer communication framework was established.
Figure 2.13: Energy Efficiency demonstrator

“High flat” position:

“High tapered” position:

“Low flat” position:

“Low tapered” position:

Figure 2.14: The 4 positions of the Energy Efficiency trailer
2.6 Evaluation Framework

In order to assess the project goal of achieving a 25% reduction of energy use per tonne\(\cdot\)kilometres, an evaluation framework has been defined in which the process of the evaluation is specified. A schematic illustration of the data sources and process steps taken during this evaluation framework is shown in Figure 2.15. The steps include real-world test measurements on road and on test tracks, simulations and economic potential evaluation.

![Activity and Deliverable Diagram](image)

Based on the vehicle testing (see Deliverable D6.2) and high fidelity simulation results (see Deliverable D2.3), a consolidated model (see Deliverable D6.3) has been used for the final assessment and reported in this report (D6.4). The improvement potential of the TRANSFORMERS innovations for selected transport mission profiles has been compared to current heavy-duty vehicle technology used for similar transport assignments.

The consolidated model makes use of test results and high fidelity simulation results in order to evaluate the effectiveness of the TRANSFORMERS innovations - separately for HoD, aerodynamics and loading efficiency innovations, as well as when combined - under various influencing parameters on the mission profile such as road type, payload and traffic conditions.

We can differentiate between two types of simulation:
- forward simulation - high fidelity simulation (including driver model tracking a target speed, and energy management),
- backwards simulation - low fidelity where vehicle speed is directly used to calculate road load, and no energy-management is modelled.

Figure 2.16 shows the trade-off of these various assessment methods in terms of fidelity and application range.
Obviously, the best way to evaluate the effectiveness of a technology or innovation is by testing it under real-life driving conditions (as described in D6.2). 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 (as described in D2.3) are highly reproducible and well suited to determine the effectiveness under a wide range of conditions. But even then, high fidelity simulations are time consuming and complex in their setup and execution. The evaluation framework described in this report makes use of the results obtained from measurements and high fidelity 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 (see Chapter 5 for more detail).

The evaluation is made in terms of

- The impact on driving dynamics,
- The impact on loading efficiency (payload capacity and load handling improvements),
- The impact on energy efficiency, CO₂ emissions and fuel consumption (including both the effects of the HoD system or the aerodynamic measures).

Furthermore, the economic potential for these innovations is evaluated for a number of selected use cases.
3 Test results using the TRANSFORMERS demonstrators

This section summarizes the results and findings from the test campaigns. The demonstrator test vehicles and equipment used for these test campaigns are extensively reported in deliverable D6.1 and deliverable D6.2.

The TRANSFORMERS demonstrators have been extensively tested on the road as well as on the test track. The following effects of the trailers have been researched and reported:

- Impact of the HoD system on the vehicle dynamics, simulated and tested by IFSTTAR, Volvo and TNO; deliverable report D4.7.
- Impact of the new trailer design and double floor on loading efficiency, tested by van Eck and P&G; deliverable report D6.2.
- Impact of the aerodynamic measures, tested by DAF; deliverable report D6.2.
- Impact of the HoD system, tested by Volvo (focus on extra-urban applications) and DAF (focus on urban applications); deliverable report D6.2.

In addition the feasibility of using load volume sensors (as an enabling technology to realize improved loading efficiency) was tested and demonstrated by Fraunhofer; deliverable report 6.2.

3.1 Vehicle dynamics testing

Assessment of the driving dynamics behaviour of the vehicle combination with the TRANSFORMERS Energy Efficiency Trailer (and HoD powertrain) is of paramount importance. This assessment was realized in the project based on seven different steps:

1. Preliminary theoretical model-based evaluation of the driving behaviour
2. Functional safety and functionality tests developed together with TÜV Rheinland
3. Commissioning tests
4. Development and testing of the brake functionality
5. Internal OEM road approval
6. Driving dynamics tests (to validate the driving dynamics models)
7. Interviewing of the drivers

These steps and their outcome are briefly described in the next paragraphs.

The theoretical model based assessment of the difference in vehicle dynamics between a generic TRANSFORMERS HoD combination and a conventional semi-trailer combination was subject of deliverable report D4.3. This describes how a literature survey was conducted which revealed the prominent manoeuvres that would cause loss of stability. These manoeuvres have been simulated with the conceptual HoD-trailer model that has been derived in WP4.3, and it was concluded that the dynamics of the HoD-concept do not differ significantly from the conventional tractor-semi trailer combination. No additional stability control measures need to be taken apart from measures such as traction control, anti-lock braking control and drive-train logic (e.g. if driver or tractor desires a braking action, the power to the electric motor(s) of the HoD-trailer should be set to zero). If, for some reason, the conventional stability controller of either tractor or semitrailer require action, the power to the HoD-trailer should be shut off as well. In those cases, also energy regeneration should be disabled.

Functional safety of the HoD system was developed by Fraunhofer IVI in cooperation with TÜV Rheinland. Commissioning of the HoD system was undertaken by Fraunhofer IVI, with low speed testing on their test track during spring 2016. Electrical safety and EMI tests were undertaken by Fraunhofer IVI, Schmitz Cargobull and TÜV Rheinland also during spring 2016. Subsequent development and testing of the brake blending functionality was undertaken by Knorr Bremse. Knorr Bremse undertook a number of braking tests to verify the safety of the braking functionality including interaction of the HoD system with the TBS and ESP during summer 2016, for example, to ensure that that the HoD system does not affect the braking system during ABS events. Other stability tests were undertaken by the project partners, for example, a deliberate but unsuccessful attempt to provoke instability in a test specially designed by FhG IVI. In this test the tractor was turned perpendicular to the trailer with the tractor wheels on wet plastic to simulate jack knifing on a low friction surface. The HoD system was engaged at full power but no movement of the tractor wheels was observed.
Following testing of safety functionality by TÜV Rheinland the TRANSFORMERS HoD trailer was registered in Germany with the HoD driveline installed. The trailer was moved between test sites with the HoD system disabled as a standard semi-trailer with German registration plates.

Both OEMs (Volvo and DAF) were in agreement that in order for the HoD system to be used in on-road fuel measurements, additional internal verification would be necessary. To simplify the testing process, Volvo agreed to focus on on-track aerodynamic testing and on-road fuel measurements looking at the effects of topography, while DAF would focus exclusively on on-track testing (aerodynamic and simulated heavy traffic conditions). For the on-road fuel measurements in Sweden it was agreed with the Swedish authorities to use manufacturer’s “green” development vehicle registration plates on the TRANSFORMERS trailer when the HoD system was enabled on the public road.

Volvo undertook internal handling, braking and performance verification tests to verify that the TRANSFORMERS combination (Volvo tractor + Schmitz Cargobull Energy Efficiency trailer) was safe to operate on the public road. The original intention had been to undertake these subjective tests driven by expert internal drivers in parallel with the driving dynamics tests, however, this was not possible due to the time window available and the availability of the personnel to instrument the tests. The TRANSFORMERS combination was subjected to a range of subjective handling and braking tests on the private Volvo test track in September 2016, i.e. the tests were not instrumented. Handling tests were driven with a special HoD system modification so that maximum propulsion power was enabled from the trailer mounted electric driveline during the handling manoeuvres to give a worst case scenario. In addition, performance verification testing was undertaken to assess the TRANSFORMERS combination from the driver’s perspective, and this resulted in an improvement of the electric braking request by the driver. After the tests were satisfactorily completed, an internal Volvo “road approval” was granted to allow the TRANSFORMERS combination to be used in on-road fuel economy measurements in Sweden with the HoD system enabled, with Swedish “green” OEM development vehicle registration plates.

Subsequently driving dynamics testing to validate the models used in D4.3 and to be used in WP5 could be performed. Those tests were defined in deliverable D6.5 and reported in D4.7. The tested manoeuvres, being a subset of the intended tests as described in D6.5 were: Single Lane-change, ISO double lane-change (“chicane”), turning manoeuvre, emergency braking. It was not possible to complete all of the necessary tests due travel plans of the visiting personnel, equipment (antenna) issues which resulted in difficulty acquiring sufficient satellite signals while testing, and poor weather including snow.

Regarding the results of the experimental tests using the HoD-trailer, it can be concluded that the dynamic behaviour of the TRANSFORMERS vehicle is very close to that of the standard vehicle in cornering or lane-changing manoeuvres. It was observed that yaw velocity, yaw angle and lateral acceleration of the TRANSFORMERS vehicle are slightly higher than the ones of the standard vehicle whereas the roll angle and velocity are equivalent. The trajectories also showed that the swing radius of the TRANSFORMERS vehicles is slightly superior to the standard vehicle’s one. It has to be emphasized that these conclusions are valid for the demo HoD-trailer only and cannot be generalized for future products with different component ratings, control architecture or control settings. However, the results with the demo HoD-trailer are promising with regards to vehicle stability and safety.

3.2 Test drivers opinion

Additional to the vehicle dynamics measurement with the TRANSFORMERS Energy Efficiency trailer, the opinions of the DAF and Volvo test drivers were gathered with regards to vehicle stability and driving characteristics. The drivers were asked for their opinion on:

- Straight ahead controllability
- Lane change controllability
- ISO chicane controllability
- Turning manoeuvre controllability
- Emergency braking manoeuvre
- Performance: power increase and decrease
- Acceleration from rest
In general it can be concluded that all five consulted test drivers perceive a same or better controllability of the TRANSFORMERS combination in comparison to a regular combination and that the controllability of the above mentioned manoeuvres is easy. The added comments of the test drivers did not show any negative impact of the TRANSFORMERS trailer on controllability during manoeuvres and braking. In many cases, the test drivers comment that the TRANSFORMERS combination drives like a regular combination, is very safe and predictable even during more evasive manoeuvres and that very little roll is perceived. Some perceive the driving behaviour even better compared to a regular combination.

The braking behaviour was perceived positive as well. Also the performance and power response was perceived equal or even better compared to a regular combination. One of the test drivers indicated that the extra power of the HoD system is not easy to feel when driving with 40 tonnes and that when driving on a flat road, requiring low torque from the diesel engine, the HoD torque was quite unstable. This instability could be felt by the driver and reveals that the control software is not optimal yet. This is also the case for power decrease without braking, which feels like an additional engine-brake, but reveals a non-optimal software strategy. One driver noted that extra traction could be beneficial in low friction conditions.

### 3.3 Loading efficiency tests

Testing has been done to find out whether the TRANSFORMERS Load Optimization Trailer as built and developed by van Eck meets the KPI’s as defined in D1.4 and repeated in this report in section 2.3. For details the reader is referred to deliverable report D6.2.

This paragraph summarizes the major achievements that were realized in terms of increased inner space (KPI1; i.e. Euro pallet per floor space, payload capacity, load factor, fill speed), loading/unloading (KPI4) and unloading/docking ease (KPI6.5).

To allow for a double floor and more pallets it was necessary to increase the inner space of the trailer (KPI1). This was realized by 121 mm, resulting in the space for an additional pallet, which gives a direct benefit of 3% additional cargo by placing 34 instead of 33 pallets on the ground floor and second floor of the trailer. This additional benefit by the increased inner length will be used in the evaluation in chapter 5, apart from the impact of the double floor.

Between all floor sections, there was enough space left for all the flex floors to move up and down without touching or damaging the pallets that are placed in front of it. As shown in Figure 3.1, a space of at least 40 mm between the end of the pallet and the beginning of the next flex floor is available. This extra space is useful for the flex floor system to move. Without the extra inner space the system of the flex-floor would have been difficult to realize. On the right of this figure it can be seen that there is a notable space behind the last pallet though it is a mixed load with a lot of pallets double stacked using the flex floor. If double stack is not used the pallets will have much more space at the end.

![Figure 3.1 The extra space behind the pallets](image-url)
The KPI on inner space further required that the internal length of the trailer is such that 34 pallets always fit in the trailer. This would give 3% more pallets. Obviously this was realized. A dock plate support was further successfully integrated in the trailer, so that the dock plate does not need to be shifted when loading the last pallets, saving a lot of operational time (fill speed) and making unloading/docking easier (KPI6).

3.3.1 Configurable roof

It proved to be very easy to set the configurable roof to its desired position with limited increase in loading time. In the timing done at P&G site in Amiens the setting of the roof is done in less than 30 seconds. This time is not depending on the number of pillars to be moved because they all start to move together. An important observation made during the test is that the batteries used to move the roof must be charged by the truck while driving, and both the truck and trailer needs to have the necessary connections for this. All possible shapes of the trailer are pre-programmed so if the driver knows the number of the shape from the freight letter he only needs to choose the correct shape number and push the start button.

The configurable roof system can also be operated through an app on a mobile phone. It is concluded that the extra time to set the roof is 1 minute: 30 seconds before (un)loading starts to move it upwards to loading position and 30 seconds after (un)loading to set it to the pre-programmed shape.

3.3.2 Flexible floor

The flex floor has proven its flexibility. Pallets that could not be double stacked previously were double stacked irrespective of the shape. With minimum training, the fork lift driver was able to quickly set the floors at the required heights and afterwards put them back to the original position. During the test it was noted that it is extremely important to leave sufficient space between the top of the pallet and the bottom of the floor. The pallets seen in the Figure 3.2 above had a space of 30 mm, but the fork lift driver still could get them out smoothly. However, when the shift changed and a new forklift driver arrived it was very difficult to remove the pallets with little gaps between the floor. To ease the process of taking the pallets out always take at least 50 mm more space than the height of the pallet. So for a pallet of 92 cm set the ends top at 100 cm as indicated by the marks. Always push the end stop in the rail. The tested time to set the floors is about 10 seconds per floor. At this point it is worth indicating that the fact that the height of the roof is adaptable (and can be increased up to 4100 mm at the dock) is making the loading/unloading the high floor easier.
From the test results, graphs were plotted that show the estimated time for (un)loading a trailer with a flex floor system (Figure 3.3 and Figure 3.4). It is obvious that when using the flex floor, above 34 pallets, the time per pallet increases. The graphs show that for the first 34 pallets, when the double floor is not used, the time needed per 4 pallets is 150 seconds (2.5 min). When the double floor is used, the time per 4 pallets is 300 seconds (5 min.), so 150 seconds per 4 pallets (one floor) extra.
3.4 DAF tests with the Energy Efficiency Trailer

In the TRANSFORMERS project DAF tested two innovations: the adaptable aerodynamics and the Hybrid on Demand system (HoD) on the Energy Efficiency Trailer. The objective of the first test was to determine the effect of the different measures for reduction of the drag force of the vehicle combinations. This was done by determining Cd*A values for the various variants at a test track. The objective of the HoD test was to measure the impact on energy consumption of the Hybrid on Demand technology as applied on the demonstrator trailer. To determine this, fuel consumption was measured with the HoD system switched on and off during a simulated dense urban traffic cycle at a test track.

3.4.1 Aerodynamics testing

Aerodynamics testing was executed according to Technical Annex VI for CO₂ declaration [2] A comparison was made between the HoD trailer and a reference trailer. For a measurement overview see the result section. The measurements were executed with an empty trailer and all measurements with the HoD trailer are executed with the boat tail folded out and folded in.

The test started with warming up the combination for more than one hour followed by an equipment check to assure the torque measuring wheels indicated 0. After this the rolling resistance was measured at 10 km/h followed by an air drag measurement at 90 km/h. The test was finished with a rolling resistance measurement at 10 km/h and drift check of the torque measurement equipment. All tests were executed with an empty trailer.

Equipment used was a GPS including trigger for determining the measurement section of the Test Track as well as Kistler torque measuring wheels. For capturing the conditions under which the tests were executed a wind meter was used to measure wind speed and direction. The road temperature was measured and also other ambient conditions like the temperature, the pressure and the humidity were determined. For air drag calculation the VECTO tool was used. The results of the aerodynamics testing are summarized in Table 3.1 below.

Table 3.1 Results of aerodynamics tests at DAF

<table>
<thead>
<tr>
<th>Tractor</th>
<th>SCB-trailer</th>
<th>Cd*A relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Roof deflector</td>
<td>Type</td>
</tr>
<tr>
<td>DAF_TF</td>
<td>standard</td>
<td>Ref</td>
</tr>
<tr>
<td>DAF_TF</td>
<td>standard</td>
<td>HoD</td>
</tr>
<tr>
<td>DAF_TF</td>
<td>standard</td>
<td>HoD</td>
</tr>
<tr>
<td>DAF_TF</td>
<td>no</td>
<td>HoD</td>
</tr>
<tr>
<td>DAF_TF</td>
<td>no</td>
<td>HoD</td>
</tr>
</tbody>
</table>

The rolling resistance of the DAF TF tractor with the TRANSFORMERS HoD trailer was measured on several days showing an average value 5.2 kg/tonne. Whereas the rolling resistance of the DAF tractor with the reference trailer was found to be 9.4 kg/tonne. This is an unexpectedly high and unrealistic value and only seen as an indication for a technical problem with the reference trailer. For this reason the Cd*A result of the reference trailer is declared invalid, and instead the “high flat, no boat tail” variant was used as a reference. Consequently this “high flat, no boat tail” reference trailer is also used in the evaluation calculation later in this report. It is worthwhile pointing out that the roof spoiler on the DAF tractor was removed in the “low” position of the trailer, as can be seen in the pictures below.
3.4.2 HoD system testing

The impact of the HoD system on fuel consumption was measured during driving a simulated dense urban traffic cycle (see Figure 3.7 below) on the DAF test track. This speed profile was developed as part of deliverable D6.5 to be representative of a situation with dense urban traffic. Fuel consumption was measured with the HoD both switched on and off in two loading conditions, i.e. empty and 15 tonne payload. To compensate for the mass of the HoD system 1.2 tonne extra weight is added during measurements with the hybrid system. During the measurements with the hybrid system switched on also the change in state of charge of the battery of the hybrid system was measured. Multiple repetitions of the tests were done to increase accuracy without using a reference truck. To obtain a good reproduction of the test, the vehicle speed was controlled automatically through a MicroAutobox. The vehicle position and speed was measured using GPS. Various signals from the vehicle CAN bus were measured including vehicle speed, vehicle odometer, fuel consumption. Also from the trailer CAN bus signals were measured including % State-of-Charge (SoC), battery voltage and current.
The results of the fuel consumption test are summarized in Table 3.2 below:

Table 3.2 Results of DAF HoD assessment

<table>
<thead>
<tr>
<th>Mass in trailer [kg]</th>
<th>HoD</th>
<th>SoC at start [%]</th>
<th>ΔSoC [%]</th>
<th>SoC Diesel equivalent [l]</th>
<th>Diesel [l]</th>
<th>SoC corrected Diesel [l]</th>
<th>Diesel saving [%]</th>
<th>SoC corrected Diesel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>on</td>
<td>NA</td>
<td>2.3</td>
<td>0.12</td>
<td>1.88</td>
<td>2.00</td>
<td>12</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>off</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16200</td>
<td>on</td>
<td>NA</td>
<td>-1.9</td>
<td>-0.10</td>
<td>3.21</td>
<td>3.11</td>
<td>3</td>
<td>5.9</td>
</tr>
<tr>
<td>15000</td>
<td>off</td>
<td>NA</td>
<td></td>
<td></td>
<td>3.31</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The numbers shown are the average results of either 4 or 5 consecutive tests. And SoC-level at the start of each series of consecutive tests was always in the range 52 < SoC [%] < 62. In both empty and loaded situation the battery state of charge (SoC) at the end of the test is different from that at the start. This difference corresponds to an electric energy consumption on top of the diesel consumption. The diesel amount that would be equivalent to this electric energy is calculated.

As the time for testing was limited, no tests were performed with maximum payload (as already indicated in deliverable report D6.5).
3.5 Volvo tests with the Energy Efficiency trailer

3.5.1 Aerodynamics testing

Aerodynamic tests have been conducted to measure impact of the different roof configurations on fuel consumption. As shown in Table 3.3 the TRANSFORMERS energy efficiency trailer (Schmitz Cargobull) has been tested with its roof in the 4 possible configurations, both with and without the boat tail and HoD system switched OFF. Fuel consumption results are compared to the same combination (Volvo FM tractor + SCB TRANSFORMERS trailer) set in the most standard configuration (high flat roof, no boat tail, no HoD). This is the configuration that comes closest to that of a standard European trailer (but includes side skirts and curved front bulkhead) for reasons discussed in Section 3.4.1.

The fuel consumption comparison between SCB TRANSFORMERS trailer in different configuration takes only into account the impact from boat tail and different roof positions. It has to be kept in mind that this trailer has already some aerodynamic optimisation such as side skirt and bulk head. Comparison to the test results with the SCB standard trailer would - in principle - have led to higher fuel economy benefit as it would have included the additional effects of skirt and bulk head as well as the differences in rolling resistance (due to lower trailer weight). However, when analysing the test data with the SCB standard trailer it was observed that this particular trailer suffered from unrealistically high rolling resistance losses as shown in the paragraph above. For this reason the resulting data are not included in this paragraph.

<table>
<thead>
<tr>
<th>Normalization vehicle</th>
<th>Test vehicle</th>
<th>configurables roof</th>
<th>Boat tail (folded out)</th>
<th>HoD</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volvo FH + Volvo Aero trailer</td>
<td></td>
<td>Front [mm]</td>
<td>Rear [mm]</td>
<td>Name</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3500</td>
<td>3500</td>
<td>low flat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3500</td>
<td>3200</td>
<td>low tapered</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4000</td>
<td>3200</td>
<td>high tapered</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4000</td>
<td>4000</td>
<td>high flat</td>
<td></td>
</tr>
<tr>
<td>Standard Schmitz Cargobull Reference trailer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 also mentions a normalization vehicle. As explained in deliverable report D6.2, the use of this vehicle is to remove the influence of changes in weather conditions (or driving behaviour) from the comparison.

Table 3.4 shows the results of this comparison.
Table 3.4 Fuel consumption benefits of different aerodynamic configuration

<table>
<thead>
<tr>
<th>Ref. SCB TRANSFORMERS (high flat, no tail)</th>
<th>60km/h</th>
<th>70km/h</th>
<th>80km/h</th>
<th>90km/h</th>
<th>100km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flat, tail</td>
<td>25.0 L/100km</td>
<td>26.2 L/100km</td>
<td>27.3 L/100km</td>
<td>30.3 L/100km</td>
<td>35.6 L/100km</td>
</tr>
<tr>
<td>Low flat, No tail</td>
<td>-2.6%</td>
<td>-4.7%</td>
<td>-5.3%</td>
<td>-6.2%</td>
<td>-6.0%</td>
</tr>
<tr>
<td>Low tapered, tail</td>
<td>1.5%</td>
<td>-0.1%</td>
<td>-0.9%</td>
<td>-3.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Low tapered, No tail</td>
<td>-5.0%</td>
<td>-2.2%</td>
<td>-5.2%</td>
<td>-9.2%</td>
<td>-7.0%</td>
</tr>
<tr>
<td>High tapered, tail</td>
<td>-2.4%</td>
<td>-2.6%</td>
<td>-3.8%</td>
<td>-6.0%</td>
<td>-2.3%</td>
</tr>
<tr>
<td>High tapered, No tail</td>
<td>-4.5%</td>
<td>-4.7%</td>
<td>-5.7%</td>
<td>-8.1%</td>
<td>-4.6%</td>
</tr>
<tr>
<td>High flat, tail</td>
<td>-0.2%</td>
<td>-1.1%</td>
<td>-2.0%</td>
<td>-3.9%</td>
<td>-1.3%</td>
</tr>
<tr>
<td>High flat, No tail</td>
<td>0.1%</td>
<td>-0.3%</td>
<td>-0.8%</td>
<td>-2.6%</td>
<td>-0.7%</td>
</tr>
</tbody>
</table>

The benefit shown in the table above is inclusive of the effect of the bulkhead and sideskirts that are present on the test configurations. Most likely, the fuel consumption benefits would be larger when compared to a standard semitrailer combination without bulkhead or sideskirts. It was not possible to give an estimate of this additional benefit.

### 3.5.2 HoD system testing

On road tests have been conducted to measure impact of the HoD system on fuel consumption, when driving on public roads. The tests were undertaken in Sweden, to assess the impact of topography on the savings. The SCB TRANSFORMERS trailer has been tested on public roads with HoD system ON and OFF. Fuel consumption when HoD system is enabled is compared to the same combination with HoD system OFF.

Two different cycles have been used. They are shown in Figure 3.8 and Figure 3.9.

![Figure 3.8 Boga cycle map](image-url)
BOGA is a 129 km long cycle and is composed of country road and highway (motorway) parts. BOB is a 262 km long cycle, only on highway. The corresponding altitude profile is shown in figure 3.10. Altitude varies widest in the BOGA cycle, but sharpest changes in altitude occur with BOB.

Tests have been performed according to two different nominal load configurations; a situation with maximum load giving 40 tonne GVW and the average European cargo load situation: 15 tonne payload. As explained in deliverable report D6.2 and shown in Table 3.5 the real weight in the HoD system OFF situation was reduced by 1 tonne to compensate for the HoD equipment extra weight (battery, electrical machine) which was around 1 tonne. This is somewhat different from the weight difference imposed at the DAF tests (1200 kg).

These 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.
Table 3.5 Fuel consumption tests vehicle configurations

<table>
<thead>
<tr>
<th>Normalization vehicle</th>
<th>Test vehicle</th>
<th>No. of Cycles Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BOGA (129 km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volvo FH + Volvo Aero trailer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GVW = 40 tonne or Cargo = 15 tonne</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Front [mm]</td>
<td>Rear [mm]</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To ensure that a minimum set of on-road tests could be completed within the timeline of the project, it was decided to stay with one strategy for HoD control. This strategy was selected as the reference HoD strategy as it seemed, at the time, to be the most promising one. In section 4.5, the results of simulations with an alternative control algorithm are presented, to analyse the future potential.

The most important test results of both the BOB and BOGA cycle are shown in the tables below.

Table 3.6 HoD energy savings in BOB tests

<table>
<thead>
<tr>
<th>TEST</th>
<th>Initial SoC</th>
<th>Change in fuel used</th>
<th>ΔSoC</th>
<th>Fuel change + SoC compensation</th>
<th>Speed difference [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref 40t without HoD</td>
<td>35.9 L/100km</td>
<td>-2.9%</td>
<td>3.0%</td>
<td>-3.0%</td>
<td>78.0 km/h</td>
</tr>
<tr>
<td>BOB 01 - 40t GVW</td>
<td>50%</td>
<td>-2.9%</td>
<td>3.0%</td>
<td>-3.0%</td>
<td>-0.2</td>
</tr>
<tr>
<td>BOB 03 - 40t GVW</td>
<td>51%</td>
<td>-3.3%</td>
<td>4.0%</td>
<td>-3.5%</td>
<td>-0.2</td>
</tr>
<tr>
<td>Ref 15t without HoD</td>
<td>30.3 L/100km</td>
<td>-2.5%</td>
<td>7.0%</td>
<td>-2.9%</td>
<td>79.9 km/h</td>
</tr>
<tr>
<td>BOB 01 - 15t payload</td>
<td>38%</td>
<td>-2.5%</td>
<td>7.0%</td>
<td>-2.9%</td>
<td>-0.1</td>
</tr>
<tr>
<td>BOB 02 - 15t payload</td>
<td>49%</td>
<td>-2.0%</td>
<td>-10.0%</td>
<td>-1.4%</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Overall, the net change in SoC was limited, with intermediate larger changes (SoC typically varied between 70 % and a lower limit of 30 %).

As a reminder: in line with the definition mentioned in previously, a positive value for ΔSoC means that the SoC value at the end of a trip is lower than at the start. The amount of fuel can be determined that would be equivalent to the electric energy release corresponding to this decrease in SoC. This so-called SoC compensation amount of fuel can then be added to the actual fuel saving. With a positive ΔSoC the total energy used for driving is larger than the fuel energy. That means that the fuel saving with SoC compensation is smaller than the actual fuel saving.
Table 3.7 HoD energy savings in BOGA tests; in this table fuel only corresponds to fuel change; other columns in line with previous table

<table>
<thead>
<tr>
<th>Test name</th>
<th>Initial SoC</th>
<th>Fuel only</th>
<th>SoC Diff</th>
<th>Fuel + SoC compensation</th>
<th>Fuel only</th>
<th>SoC Diff</th>
<th>Fuel + SoC compensation</th>
<th>Fuel only</th>
<th>SoC Diff</th>
<th>Fuel + SoC compensation</th>
<th>Fuel only</th>
<th>SoC Diff</th>
<th>Fuel + SoC compensation</th>
<th>Fuel only</th>
<th>SoC Diff</th>
<th>Fuel + SoC compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. BOGA</td>
<td>-</td>
<td>37.1 L/100km</td>
<td>48.7 L/100km</td>
<td>26.7 L/100km</td>
<td>41.6 L/100km</td>
<td>39.4 L/100km</td>
<td>48.2 L/100km</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOGA 1</td>
<td>42%</td>
<td>-3.1%</td>
<td>-1%</td>
<td>-4%</td>
<td>4.7%</td>
<td>3.3%</td>
<td>7%</td>
<td>-1.8%</td>
<td>6%</td>
<td>-10%</td>
<td>-3.5%</td>
<td>6%</td>
<td>-10%</td>
<td>-3.5%</td>
<td>6%</td>
<td>-10%</td>
</tr>
<tr>
<td>BOGA 2</td>
<td>41%</td>
<td>-3.2%</td>
<td>-1%</td>
<td>-1%</td>
<td>1.1%</td>
<td>1.4%</td>
<td>6%</td>
<td>-2.8%</td>
<td>6%</td>
<td>-10%</td>
<td>-2.5%</td>
<td>2.4%</td>
<td>11%</td>
<td>-12.6%</td>
<td>5%</td>
<td>-11%</td>
</tr>
<tr>
<td>BOGA 3</td>
<td>59%</td>
<td>-0.8%</td>
<td>-1%</td>
<td>-18%</td>
<td>7.7%</td>
<td>-7.1%</td>
<td>-21%</td>
<td>1.2%</td>
<td>2.0%</td>
<td>0.0%</td>
<td>9%</td>
<td>-12.1%</td>
<td>-2.7%</td>
<td>-11%</td>
<td>1.6%</td>
<td>-3.0%</td>
</tr>
<tr>
<td>BOGA 4</td>
<td>50%</td>
<td>-4.6%</td>
<td>-10%</td>
<td>-3.5%</td>
<td>-3.5%</td>
<td>-9.4%</td>
<td>-17%</td>
<td>-2.2%</td>
<td>0.2%</td>
<td>8%</td>
<td>-10.9%</td>
<td>-4.7%</td>
<td>-10%</td>
<td>-0.6%</td>
<td>-5.3%</td>
<td>2%</td>
</tr>
</tbody>
</table>

In the above tables, there are no values mentioned for the KPI-numbers KPI3 and KPI4. These numbers have been determined and are mentioned in deliverable report D6.2. Preference was given here to give the results in terms of (equivalent) fuel consumption benefits.
4 High fidelity simulations on optimal HoD configuration

In the second half of 2015 an investigation was made with the goal to choose the most relevant routes for evaluation of TRANSFORMERS results. As the project does not have possibility to perform large scale real-life testing, one of the main indications of benefits delivered by TRANSFORMERS solutions will be obtained from high fidelity simulations, with the models validated by the actual on-road test results.

4.1 Aim and approach

The aim of the simulations was to determine an optimal Hybrid-on-Demand configuration to achieve maximum fuel savings potential. To achieve this goal key parameters were picked and it was decided in which way they could be varied. This resulted in a high number of variations that were represented in a simulation matrix. Variations of the original configurations and combination of variations were simulated for each of the five routes (presented in section 2.4) to find the most promising configurations. Over the course of the project about 700 high fidelity holistic simulations have been done.

4.2 Model description

The simulation model, which was developed during this project, consists of different components. An overview can be seen in Table 4.1. They were coupled together in the co-simulation platform AVL Model.CONNECT to perform holistic simulations. With this system it was possible to include components remotely from different organisations, do variant management (e.g. using different battery models without changing the holistic model), and case management to simulate a high number of variations.

The truck components are parametrized in a way that they represent a generic truck rather than either the Volvo or DAF trucks specifically, but the HoD components show the same behaviour as the real HoD system. This was evaluated during the project by comparing the results of the simulations to the results of the Volvo on-road tests.

<table>
<thead>
<tr>
<th>Component</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>VIF</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>VIF</td>
</tr>
<tr>
<td>Transmission (Truck)</td>
<td>VIF</td>
</tr>
<tr>
<td>Transmission (Trailer)</td>
<td>VIF</td>
</tr>
<tr>
<td>ICE</td>
<td>TNO</td>
</tr>
<tr>
<td>Driver</td>
<td>VIF</td>
</tr>
<tr>
<td>TDMS/VEMS</td>
<td>FhG</td>
</tr>
<tr>
<td>Driving Dynamics</td>
<td>TNO</td>
</tr>
<tr>
<td>EMG</td>
<td>VIF</td>
</tr>
<tr>
<td>Battery</td>
<td>VIF</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>VIF</td>
</tr>
<tr>
<td>Cooling System</td>
<td>VIF</td>
</tr>
</tbody>
</table>

In Figure 4.1 the Model.CONNECT model for the HoD Truck/Trailer combination can be seen. On the far left side is a block that contains all the parameters 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 4.1 AVL Model.CONNECT Model
4.3 Model input

4.3.1 Vehicle parameters and hybrid configurations

A number of parameters were defined that should be varied to see which configurations or combinations of the HoD driveline perform best. A major focus was on HoD system parameters such as electric motor/generator (EMG) power or battery capacity, to find the best configurations for each route or type of transport mission (see Table 4.2). Also different routes were simulated. These routes have different altitude and speed profiles and the traffic conditions were varied if data was available.

Table 4.2 Main variations

<table>
<thead>
<tr>
<th></th>
<th>Max. EMG power [kW]</th>
<th>Battery size [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 (payload in kg)</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>15000 (payload in kg)</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>40000 (gross combination weight (differs between cases))</td>
<td>160</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.3 shows the weight of the tractor and the different trailer configurations.

Table 4.3 Vehicle parameters: weight

<table>
<thead>
<tr>
<th>Configuration</th>
<th>weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractor (empty)</td>
<td>7000</td>
</tr>
<tr>
<td>Trailer (no aerodynamic features / no HoD)</td>
<td>6700</td>
</tr>
<tr>
<td>Trailer (aerodynamic features / no HoD)</td>
<td>7100</td>
</tr>
<tr>
<td>Trailer (aerodynamic features / HoD)</td>
<td>8250</td>
</tr>
<tr>
<td>Trailer (no aerodynamic features / HoD)</td>
<td>7850</td>
</tr>
<tr>
<td>Trailer (double load floor)</td>
<td>+1200</td>
</tr>
</tbody>
</table>

According to the specifications of the TRANSFORMERS trailer, the combination of HoD system and additional aerodynamic components has an additional weight of 1150 kg (550 kg when excluding the battery). The weight of the battery system is 30kg per kWh due to the heavily engineered battery box. For commercially available products the battery cell weight at system level (incl. packaging material) is in the order of 10 kg/kWh. The reduction in battery system weight will be considered in the future potential of the hybrid system.

Table 4.4 Hybrid configurations: additional vehicle weight due to batteries

<table>
<thead>
<tr>
<th>Battery</th>
<th>Add. weight of current system [kg]</th>
<th>Add. weight of future system [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kWh</td>
<td>550+30*5 = 700</td>
<td>550+10*5 = 600</td>
</tr>
<tr>
<td>10 kWh</td>
<td>550+30*10 = 850</td>
<td>550+10*10 = 650</td>
</tr>
<tr>
<td>15 kWh</td>
<td>550+30*15 = 1000</td>
<td>550+10*15 = 700</td>
</tr>
<tr>
<td>20 kWh</td>
<td>550+30*20 = 1150</td>
<td>550+10*20 = 750</td>
</tr>
<tr>
<td>40 kWh</td>
<td>550+30*40 = 1750</td>
<td>550+10*40 = 950</td>
</tr>
</tbody>
</table>

4.3.2 Route specifications

Simulation results may vary heavily depending on the environment (including route) used for testing solutions. Thus it is essential to select the routes which represent relevant driving conditions.

In the following section, the routes and their altitude profiles that were used for simulations will be described. The routes used are selected according the characteristics and scenario’s as defined in the early stages of the project and presented in paragraph 2.4, wherever data was available. Some of the routes were shortened to keep the simulation time lower and allowing the number of simulations to be increased.

The shortened routes were chosen such that the start altitude and end altitude is nearly the same, see Table 4.5 below. This is important to get representative energy calculations and simulation results. Also an energy calculation was done to make sure that the energy ratio of the route stays the same. The energy ratio is the
ratio of traction energy to braking energy. It was calculated by using the altitude profile of the routes and assuming a constant speed over the whole route. Losses in the driveline were neglected.

Table 4.5 Altitude changes between start and stop of different WP2 simulated routes

<table>
<thead>
<tr>
<th>S1</th>
<th>Start Altitude [m]</th>
<th>End Altitude [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>S3</td>
<td>311</td>
<td>318</td>
</tr>
<tr>
<td>S4</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>S5</td>
<td>871</td>
<td>869</td>
</tr>
<tr>
<td>S6</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Motorway driving - flat surface (S1)
This route represents a flat road on the motorway. It is 157 km long and with the exception of a small hill in the beginning the altitude changes over the distance are very low (see Figure 4.2).

Motorway driving - mixed environments (S2)
This is the longest road. It is motorway only and represents flat parts, small and steep hills. The distance of the shortened route is 363 km (see Figure 4.3). The short route, which was used in the simulations, is represented by the green square.

Route with frequent elevation changes (S3)
This route is also motorway only. The altitude profile of Figure 4.4 shows several up-/downhill parts over a distance of 119 km. The short route, which was used in the simulations, is represented by the green square.
**Steep hills (S4)**
This motorway route is defined by a long uphill part, followed by some smaller elevation changes and a longer downhill part. The short route, which was used in the simulations, is represented by the green square (see Figure 4.5).

![Figure 4.5 Altitude profile of S4](image)

**Urban driving (S5)**
The last route represents an urban driving scenario (in this case Amsterdam; see Figure 4.6). It is a short, low velocity route. Several traffic conditions were considered to simulate low/medium/high traffic (see Figure 4.7).

![Figure 4.6 Altitude profile of S5](image)

**Figure 4.7 Velocity profiles of the three different traffic cases for S5**

**Summary of available routes**
Detailed simulations have been made for different combinations of road type, topology and traffic density (or congestion). But not all possible combinations have been calculated with the high fidelity holistic simulations models. The tables below give an overview of the combinations that have been calculated and their corresponding route name.
Table 4.6 Available cycles for motorway

<table>
<thead>
<tr>
<th>Road</th>
<th>motorway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>Flat</td>
</tr>
<tr>
<td>Congestion</td>
<td>low</td>
</tr>
<tr>
<td>Route name</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4.7 Available cycles for mixed environments

<table>
<thead>
<tr>
<th>Road</th>
<th>mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>Flat</td>
</tr>
<tr>
<td>Congestion</td>
<td>low</td>
</tr>
<tr>
<td>Route name</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4.8 Available cycles for urban environments

<table>
<thead>
<tr>
<th>Road</th>
<th>urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>Flat</td>
</tr>
<tr>
<td>Congestion</td>
<td>low</td>
</tr>
<tr>
<td>Route name</td>
<td>S5</td>
</tr>
</tbody>
</table>

Different weather or road conditions were not considered in the simulations. Road quality as well as weather conditions were estimated to be good.

4.4 Model results for case 3

The simulations were separately done for each of the five scenarios. The variations focused on different payloads, maximum electric motor/generator power and battery size. For some scenarios the available data also allowed traffic condition variations. In particular, this is important for the urban route, because traffic has a big influence in this scenario. All simulations were done using the so called case 3 HoD strategy, which was used in the tests as presented in chapter 3.

While the empty and average cases always have the same payload, the payload of the full case is calculated in such a way that a total weight of 40 tonnes is reached. The change in payload then balances the weight change that results from the weight of the HoD system (and its battery system weight). The aerodynamic variations were not considered for these simulations, because the focus was on the HoD system and which combination would show the most benefits.

The HoD system was adjusted in the way as it was for the Volvo on-road tests. That means that the EMG also has a torque limitation for boosting (50Nm for the 40kW EMG and 100Nm for all other EMGs). The battery state of charge at the beginning of each route was set to 35%. It was decided that this would be a realistic value, with the assumption that the vehicle would empty the battery during driving (empty means 32% because the limit was set to this value), but due to the braking when the vehicle reaches its destination it will recuperate a few percent.

In the simulations a big focus was placed on different combinations of maximum EMG power and battery size to see which combinations would be most promising. A smaller battery has a weight advantage, however, for the simulations it was neglected that a 5 kWh battery is maybe not capable to deal with 240 kW of power.

In the tables below a couple of combinations are listed. The first three columns show the battery size, maximum EMG power and payload of this configuration. The next column shows the improvement of the key performance indicator 3 (KPI3) in percent compared to the reference case without the HoD system. The last column shows the fuel saving in percent compared to the reference vehicle over the whole distance. This value is SoC corrected, which means that the delta SoC was converted to fuel. This was done in the same way Volvo did it for their on-road tests.

4.4.1 Model Results for S3 (frequent elevation changes)

Table 4.9 shows the results for three battery/EMG combinations and two different payloads/weights. Full trailer means that the gross combination weight is 40 tonnes. This results in different payloads for the cases (depending on the weight of the battery). KPI3 uses the payload for calculation, not the total weight. This is the reason why KPI3 shows less improvement for full cases than for fuel saving.
The HoD trailer shows improvements for all cases, especially with a higher maximum EMG power. Since the route for S3 has only small hills, it is possible to reduce the battery size. This has the positive effect of less battery weight.

Table 4.9 S3 - Medium Traffic

<table>
<thead>
<tr>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 240</td>
<td>Average</td>
<td></td>
<td>2,7475</td>
<td>1,7191</td>
</tr>
<tr>
<td>10 240</td>
<td>Full</td>
<td></td>
<td>1,5868</td>
<td>3,6089</td>
</tr>
<tr>
<td>20 80</td>
<td>Average</td>
<td></td>
<td>1,6859</td>
<td>0,6563</td>
</tr>
<tr>
<td>20 80</td>
<td>Full</td>
<td></td>
<td>-1,4046</td>
<td>1,9195</td>
</tr>
<tr>
<td>20 240</td>
<td>Average</td>
<td></td>
<td>2,8565</td>
<td>1,8109</td>
</tr>
<tr>
<td>20 240</td>
<td>Full</td>
<td></td>
<td>0,3193</td>
<td>3,5462</td>
</tr>
</tbody>
</table>

4.4.2 Model Results for S4 (steep hills)

The route of S4 has much more recuperation potential due to its big altitude changes. In this case it is important to have a bigger battery because of the long downhill part, which gives the HoD system a good opportunity to recuperate more energy. Fuel savings of 13%-14% can be achieved in comparison to the reference vehicle (see Table 4.10).

Table 4.10 S4 - Medium Traffic

<table>
<thead>
<tr>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 240</td>
<td>Average</td>
<td></td>
<td>8,8517</td>
<td>8,6662</td>
</tr>
<tr>
<td>10 240</td>
<td>Full</td>
<td></td>
<td>7,5718</td>
<td>7,8434</td>
</tr>
<tr>
<td>20 80</td>
<td>Average</td>
<td></td>
<td>6,8094</td>
<td>6,6620</td>
</tr>
<tr>
<td>20 80</td>
<td>Full</td>
<td></td>
<td>6,6586</td>
<td>8,0474</td>
</tr>
<tr>
<td>20 240</td>
<td>Average</td>
<td></td>
<td>14,4060</td>
<td>13,9565</td>
</tr>
<tr>
<td>20 240</td>
<td>Full</td>
<td></td>
<td>12,1723</td>
<td>13,2297</td>
</tr>
</tbody>
</table>

4.4.3 Model Results for S5 (urban)

The urban scenario has also a lot of recuperation potential due to many braking events because of traffic and traffic lights. Simulations showed best results with a higher EMG power (see Table 4.11).

Table 4.11 S5 - Medium Traffic

<table>
<thead>
<tr>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 240</td>
<td>Average</td>
<td></td>
<td>14,2288</td>
<td>14,2114</td>
</tr>
<tr>
<td>10 240</td>
<td>Full</td>
<td></td>
<td>9,5911</td>
<td>12,9055</td>
</tr>
<tr>
<td>20 80</td>
<td>Average</td>
<td></td>
<td>4,6491</td>
<td>4,6677</td>
</tr>
<tr>
<td>20 80</td>
<td>Full</td>
<td></td>
<td>-0,7010</td>
<td>4,1556</td>
</tr>
<tr>
<td>20 240</td>
<td>Average</td>
<td></td>
<td>17,1120</td>
<td>17,1531</td>
</tr>
<tr>
<td>20 240</td>
<td>Full</td>
<td></td>
<td>7,7426</td>
<td>12,2295</td>
</tr>
</tbody>
</table>

4.4.4 Conclusion

The high fidelity simulations had the purpose to look at different HoD system configurations to find the most promising cases for several defined scenarios. Those scenarios represent real routes and therefore the results show in which direction further developments should go.
The simulations that were done at this stage of the project are high fidelity simulations. Due to the higher complexity the simulation time was quite high (1 hour to 13 hours depending on the route) and therefore the number of simulations was limited (despite that around, 700 cases have been simulated).

The results of the high fidelity simulations give a good overview of the potential of several configurations on different type of routes and served also as an input for further low fidelity evaluation done by TNO. These calculations also use the results of the more specific DAF and Volvo tests, as well as the P&G/VEG loading and unloading tests.

4.5 Model results for case 4 and plug-in scenarios

During the Volvo on-road testing period different HoD strategies were implemented. The case 3 strategy (was used in the tests, see sections 3.5.2. and 4.4) looked promising and due to lack of time it was decided to run the tests with this strategy only. However, at the end of the test period some short tests with another strategy, called “case 4”, showed even more promising results. In order to assess the improvement potential, it was decided to re-run a few simulations using the case 4 strategy. Tables 4.12, 4.14 and 4.16 show the direct comparison to the case 3 simulations. As before the fuel saving values (and KPI3) are SoC corrected.

Furthermore the same cases were simulated again using case 3 strategy but considering a plug-in scenario. That means, it is assumed that the battery can be charged externally, e.g. at the distribution centre or on a motorway service area. Since, the routes are relatively short and charging the battery takes more than half an hour it was decided that a realistic plug-in scenario is defined by leaving the distribution centre with an almost fully charged battery (initial SOC 80%) but no recharging is done along the route. The idea of plug-in is to make use of electrical energy from the grid in order to reduce fuel consumption. That means, that the fuel savings of the plug-in scenario must be considered without SoC correction, otherwise the benefit of the plug-in scenario is eliminated. For the sake of fairness the results are compared to the case 3 no plug-in fuel savings without SoC correction too. It makes no sense to compare the KPI3 values, because they are by definition SoC corrected values (see section 2.3.4).

4.5.1 Model Results for S3 (frequent elevation changes)

Table 4.12 shows that the plug-in scenario can give an additional 4% fuel savings in comparison to the no plug-in case. It also can be seen that the saving depends on the battery size. The bigger the battery the more energy from the grid is available for boosting. The recuperation potential depends only on the route characteristics and the payload. Notwithstanding, cases with full payload show almost the same or even less savings as cases with average payload. The reason is, that due to high SoC initial state the battery is often close to the limit where no or only reduced recuperation can take place. That means that the cases with full payload miss more opportunities for recuperation than cases with average payload.

Table 4.12 Plug-in results for S3 (case 3 plug-in in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>Fuel Saving in % (not SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>plug-in</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>2.1224</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>1.9348</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>4.1880</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>3.9916</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>3.9630</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>4.0084</td>
</tr>
</tbody>
</table>

Control strategy case 4 results in an additional savings of 2.8% in comparison to case 3 for the best configurations (see Table 4.13). These values are SoC corrected, that means the case 4 strategy can make more usage of the recuperation potential of the route than the case 3 strategy.
### Table 4.13 Case 4 results of S3 (case 4 conventional in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Plug-In</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>2.5272</td>
<td>2.4669</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>2.7997</td>
<td>2.7162</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>1.1386</td>
<td>1.1164</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>1.3386</td>
<td>1.3008</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>2.0485</td>
<td>2.0050</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>2.8225</td>
<td>2.7441</td>
</tr>
</tbody>
</table>

### 4.5.2 Model Results for S4 (steep hills)

Due to the high recuperation potential of S4 the benefit of the plug-in scenario is lower than for S3. This can be seen by comparing Table 4.14 with Table 4.12. The main reason for this is that the upper SoC limit is reached early because of the higher initial SoC. Therefore the full recuperation potential of the route cannot be used. It also explains why the simulations with the smaller EMG (80kWh) show more improvement than the simulations with the bigger EMG. The best case gives an additional saving of 1.1% in comparison to the conventional battery. As before, simulations with full payload result in lower savings due to the higher recuperation and the battery limits (see section 4.51).

### Table 4.14 Plug-in results for S4 (case 3 plug-in in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>Fuel Saving in % (not SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug-in</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>0.6909</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>0.5666</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>1.1135</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>0.6526</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>0.9741</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>0.4358</td>
</tr>
</tbody>
</table>

Table 4.15 shows the results using control strategy case 4 (no plug-in battery). It can be seen that the new strategy fits very good for S4. Additional savings up to 4.7% in comparison to case 3 are possible. Since the values are SoC corrected the improvement should be more or less independent of the initial Soc.

### Table 4.15 Case 4 results of S4 (case 4 conventional in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Plug-In</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>2.7818</td>
<td>2.6597</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>4.9030</td>
<td>4.6690</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>1.4164</td>
<td>1.3688</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>1.3922</td>
<td>1.3308</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>2.8921</td>
<td>2.7716</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>4.3896</td>
<td>4.1541</td>
</tr>
</tbody>
</table>

### 4.5.3 Model Results for S5 (urban)

The plug-in results for S5 are very interesting (see Table 4.16). As might be expected most of the simulations with the 20kWh battery show better results than simulations with the 10kWh battery because it starts with much more energy for boosting. In the best case an additional saving of 3.4% in comparison to
the conventional battery is reached. It has to be mentioned that due to the short distance of the route (4.5 km), small changes in fuel consumption have a bigger impact on the results presented in percent. For example: a reduction of 0.12 liter fuel results in 3% fuel savings because the whole consumption of the route is about 4 liter fuel.

Table 4.16: Plug-in results for S5 (case 3 plug-in in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>Fuel Saving in % (not SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug-in</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>1.3708</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>2.9152</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>2.4538</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>0.7628</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>3.4542</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>3.4749</td>
</tr>
</tbody>
</table>

Table 4.15 shows the results of the simulation with control strategy case 4 in comparison to case 3. These simulations show that for a higher maximum EMG power additional savings of up to 4.1% can be achieved. For the 80kWh only a small improvement can be seen.

Table 4.15 Case 4 results of S4 (case 4 conventional in comparison to case 3 conventional)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Battery Size [kWh]</th>
<th>EMG Power [kW]</th>
<th>Payload</th>
<th>KPI3 ratio in %</th>
<th>Fuel Saving in % (SoC corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-Plug In</td>
<td>10</td>
<td>240</td>
<td>Average</td>
<td>4.0287</td>
<td>4.0708</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
<td>Full</td>
<td>3.9900</td>
<td>4.0362</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Average</td>
<td>0.5473</td>
<td>0.5098</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>Full</td>
<td>0.2927</td>
<td>0.2910</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Average</td>
<td>0.2365</td>
<td>0.1619</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>240</td>
<td>Full</td>
<td>4.1438</td>
<td>4.1406</td>
</tr>
</tbody>
</table>

4.5.4 Conclusion

The quick-scan reveals that control strategy case 4 suits very good to routes with high recuperation potential like S4. Almost 5% additional savings in comparison to case 3 are possible. Nevertheless, also for the highway route S3 an additional saving of 2.8% is achieved. For the urban route S5 in some cases an additional saving of 4% is reached.

For routes with lower recuperation potential like S3 an additional saving of 4% is possible in the plug-in scenario. The savings might be even higher if the boost torque limitation would be modified for higher SoC levels. For routes with high potential for recuperation the benefit of a plug-in battery is lower, due to the good recuperation. It also should be mentioned that the consumed energy was not differentiated in this quick-scan. In case of plug-in batteries a certain amount of energy would be delivered by (renewable) electric energy, which is cheaper than diesel and would shift the results again in favour of plug-in batteries because of lower costs.

To sum up there is still a high potential for improvements using different control strategies for different routes. The strategy should also consider the 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, depending on the type of route. Something like a predictive energy management systems can take road and traffic conditions into account and would be able to optimize fuel and energy savings. This approach may enable the full potential of hybrid drivelines in typical road based haulage applications.
5 Evaluation results

The test measurement results (Ch.3) show the potential of single TRANSFORMERS innovations for a limited number of configurations and test routes. The simulation results (Ch.4) investigated the effectiveness of the HoD under different route conditions, and for variations in the configuration of the system. Chapter 5 analyses these results in more detail in order 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. Chapter 5 focusses on the evaluation of 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 CO₂ is equivalent to the impact on fuel consumption, the latter is used as the primary metric in Chapter 5. The key inputs to the evaluation are described, the saving potential of the individual and combined TRANSFORMERS innovations are discussed, along with future potential.

After the introduction in 5.1 and description of the key input in 5.2, the saving potential of the TRANSFORMERS innovations are discussed in 5.3, ending with the potential of the combined innovations. Finally, the future potential is briefly discussed in 5.4 and the key conclusions are summarized in 5.5.

5.1 Aim and approach

The measurement results discussed in the previous chapters show the potential of single TRANSFORMERS innovations for a fixed number of configurations and a set of cycle conditions. Furthermore, the simulation results in the previous chapter have researched the effectiveness of HoD configurations under different conditions (congestion, payload, road type). The aim of this chapter is to analyse these results in more detail in order to understand at 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?

In order to compare and combine the vast amount of results from the test campaign and the ViF simulations, a harmonized vehicle model is used. This model makes use of a Willans lines approach, which describe the relation between the power demand at the wheels and the fuel rate of the engine. The model is calibrated and validated against the detailed simulation results provided in the previous chapters for different duty cycles and payloads. The model results, reported in terms of MJ/tonne*kilometres (KPI3), for hybrid and aerodynamics innovations are then compared and related to measurement results from DAF and VOLVO. Loading efficiency is modelled in terms of additional payload that can be carried during the trip. The simulation results are used in the following chapter as the basis for the economic assessment.

The following subsections document the approach and evaluation results for all TRANSFORMER technologies in more detail.

5.2 Model description and simulation inputs

The high-fidelity and detailed ViF vehicle model (described in the previous chapter) includes a driver model and is a so-called forward simulation model. In contrast, the evaluation framework in this chapter – which aims to provide an overview of the fuel savings potential of the single, but also the combined TRANSFORMERS innovations – uses vehicle speed as an input (backward simulation) and uses a simplified powertrain model. This methodology is chosen to assess a wide variety of applications in a short time, as was explained in the "evaluation framework" paragraph 2.6. This vehicle model makes use of Conventional and Hybrid Willans lines to describe the relation between road load and fuel consumption. The road load is calculated using the same vehicle parameters, mission profiles and road load equations as used by ViF (see the previous chapter and Appendix 0). The approach and key assumptions to modelling the effects of HoD, aerodynamics and loading efficiency is described below.

5.2.1 Hybrid efficiency

The effect of powertrain hybridization on fuel consumption is a complex function of the interaction between powertrain configuration, component sizing, energy management and road load power demand, among other things. In the high-fidelity ViF simulations, the full complexity of the hybrid system is modelled. In the modelling approach of the evaluation framework, however, the goal is to capture the most important interactions of hybrid powertrain configuration and combine it with other TRANSFORMER innovations. As such the focus lies on determining a usefully accurate estimate of the potential fuel savings for many different powertrain configurations and different use cases.
To achieve this level of functionality, the Willans-line approach has been extended to the effect of powertrain hybridization. The rationale used is that, in the case of a trailer-based Hybrid on Demand system where there is only a through-the-road connection between conventional and electrical powertrain modules, the fuel saving due to the hybrid system is proportional to the amount of energy that can be recuperated during braking events. This energy can be used at a later time in motor-assist mode, thereby offsetting work from the conventional powertrain, and saving fuel. A conventional Willans-line model can be used for positive road loads, as described in Appendix A2. This model is extended for negative road loads to account for the effect of the Hybrid on Demand axle (see Appendix A3). The following assumptions are used to model the effect of a Hybrid on Demand powertrains:

- **Assumption 1**: Fuel savings due to the Hybrid on Demand trailer are due to offsetting work by the internal combustion engine. Changes in efficiency of the ICE due to a different load cycle in the hybrid configuration are not considered.

- **Assumption 2**: The amount of engine work offset by the HoD trailer is directly proportional to the amount of energy regenerated during braking events. All energy recuperated by the hybrid system is directly translated into a fuel saving, using the corresponding hybrid efficiency. The situation where the limits of battery capacity have a significant effect on the ability of the vehicle to recuperate braking energy is therefore not accurately represented by the hybrid Willans-line model. In this project, the S4 steep hills route has the longest extended recuperation period, where the battery capacity can be a limiting factor. For the larger battery capacity cases, this is not a limiting factor. For the smaller batteries however, this can affect the accuracy of the hybrid Willans-line model.

- **Assumption 3**: The maximum power available for regeneration during braking events is limited by the power and torque limits of the electric motor generator of the Hybrid on Demand trailer. A larger motor-generator will therefore allow more fuel savings, as a larger share of the braking energy can be recuperated.

- **Assumption 4**: Engine on/off is not a function of the HoD truck, idling and/or auxiliary losses are always present, also during standstill, coasting or braking events.

- **Assumption 5**: Losses in energy conversion and transmission are accounted for where possible by using the available data from high fidelity simulations. Their effect will be implicitly included into the hybrid powertrain efficiency.

- **Assumption 6**: For fair fuel consumption comparison with high fidelity simulation or test results, a fuel consumption correction should be made for the high-fidelity simulation if the battery SoCs at the begin and the end of the cycle are different. In this correction an equivalence ratio of 0.23 \([\text{l/kWh}]\) is used. The derivation of this value is described in Appendix A4.

With this approach, fuel savings due to hybridization on a particular drive cycle are accounted for through ‘virtual’ negative fuel rates during braking events. A detailed description of the hybrid Willans line model is presented in Appendix A, including a validation with high-fidelity ViF simulations.

### 5.2.2 Aerodynamic efficiency

In contrast to a hybrid drivetrain, the effect of advanced aerodynamics on fuel consumption is a less complex matter, since it has a direct influence on the road load (see Appendix A). With an improved aerodynamics coefficient \( \text{Cd*A} \) the aerodynamics term \( \frac{1}{2} \rho \text{Cd*A*v}^2 \) is reduced which results in a lower fuel consumption. However, improved aerodynamics also comes at a penalty of additional weight of the empty vehicle which results in an increase of the rolling resistance as well as the inertial and gradient forces. Depending on the weight penalty, this effect can be large.

The advanced aerodynamics of the TRANSFORMERS Energy Efficiency Trailer incorporates four improvements in comparison to a standard tractor-semitrailer combinations:

- A. Curved front bulk head
- B. Side skirts
- C. Configurable roof
- D. Boat tail

In the project, however, only the flexible roof and the boat tail were evaluated, since the bulk head and side skirts were already integrated in the reference vehicle. Based on the measurements, the additional weight and the aerodynamic coefficient was determined for different positions of the roof in combination with boat tail and without. The effects of advanced aerodynamics on \( \text{Cd} \) are displayed in Table 5.1. The additional weight of the flexible roof and the boat tail was approximately 180kg.
Table 5.1 Coefficients of aerodynamic drag at different improvement levels (also see table 3.1)

<table>
<thead>
<tr>
<th></th>
<th>CdxA relative</th>
<th>CdxA absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>boat tail</td>
<td>no boat tail</td>
</tr>
<tr>
<td>High flat</td>
<td>91.4%</td>
<td>100%</td>
</tr>
<tr>
<td>High tapered</td>
<td>85.7%</td>
<td>91.9%</td>
</tr>
<tr>
<td>Low flat</td>
<td>87.1%</td>
<td>92.2%</td>
</tr>
<tr>
<td>Low tapered</td>
<td>86.2%</td>
<td>90.8%</td>
</tr>
</tbody>
</table>

From the C*d*A values shown above, it can already be concluded that the highest reduction in aerodynamic drag (and therefore fuel consumption) can be achieved with a high tapered roof in combination with the boat tail: aerodynamic drag reduction amounts to roughly 14.3%. The lowest potential is achieved with the high flat boat-tail: 8.6%. In the high-tapered and no boat-tail configuration, drag reductions of nearly 9% can be achieved. In the simulations below this case will be referred to the medium potential solution, since it is applicable in combination with load efficiency improvements. While higher savings in comparison to the medium potential can be achieved, this always reduces the loading capacity of the trailer. Since the highest potential is already captured with the high-tapered + boat-tail, no further differentiation was applied.

5.2.3 Loading efficiency

The effectiveness of loading efficiency is largely determined by the initial and maximum payload of a vehicle in combination with the additional loading space in terms of the loading metric. The loading metric can be square meters [m²], cubic meters [m³], pallet spaces [#pallets], rolling containers [#RCs], etc.

In the case of palletized goods, the loading metric is pallets. In the measurement campaigns of Van Eck and P&G, it was shown that the double floor in the load optimization trailer had the potential of shipping between 5 and 15 additional pallets. This assumes that the pallets in a conventional trailer could not be double stacked, which is not always the case. The range between these numbers can be related to the difference in the initial payload. At an initial payload of 20.7 tonnes only 5 additional pallets could be fitted (approximately 3.3 tonnes) since the max. payload of 24 tonnes was reached. When staying far below this limit 15 additional pallets could be fitted (approximately 3 tonnes). In the 5 pallets case, the packaging density was approximately 360 kg/m³ [660 kg/pallet]. In the 15 pallets case, the packaging density was close to 120 kg/m³ [200 kg/pallet]. In both cases, the truck was filled with approximately 55-60 m³ of products.

The cases above nicely show the dependencies of the effectiveness of loading efficiency in terms of initial and maximum payload as well as the additional loading space. This is best explained with the following table. Considering standard dimensions of a semitrailer (approximately 13.6m length, 2.5m height, 2.5 meters width) the max. volume that can be carried is limited to 85 m³. The GVW cannot exceed 40 tonnes, which means for an empty vehicle-combination of 15 tonnes the payload is limited to 25 tonnes. The table below indicates the boundaries that are faced with loading efficiency for a reference volume of 60 m³. Under the current EU legislation, loading efficiency measures have no effect for product densities above 400 kg/m³. The reason for this is that at a reference volume of 60 m³, the operation is limited by the max. GVW (see fields in red). At 400 kg/m³, about one tonne of extra volume can be stored without exceeding the max. GVW. The lower the product density becomes the more volume (and thus weight) can be loaded. At a product density of 200 kg/m³, up to 5 tonnes of additional payload can be loaded. However, the additional loading efficiency is not unlimited. The lower the densities are the less steep the additional payload increase becomes. The upper limit of additional payload reaches its saturation at 5 tonnes.
5.3 Savings potential of TRANSFORMER innovations

When taking into account all configurations of the TRANSFORMERS innovations, a large set of configurations of the individual innovations is generated: 8 configurations for aerodynamics, 3 for hybrid and in theory 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 was calculated 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: 1 tonne additional payload
  - Middle potential results: 3 tonnes additional payload
  - High potential results: 5 tonnes 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 electric-motor-generator (EMG) and 20kWh battery
  - Middle potential results: 160kW and 20kWh
  - High potential results: 240kW and 10kWh

The choices for assigning specific configurations to low, medium and high have been discussed in the section 5.2. Summarizing the rationale behind these choices:

- Loading efficiency (see 5.2.3): although in some cases more than 5 tonnes additional payload can be loaded using the double floor, the upper limit of additional payload reaches its saturation at 5 tonnes with a product density of 200 kg/m³. 3 and 1 tonnes additional payload were chosen for obvious reasons.

- Aerodynamic measures (see 5.2.2.): the highest drag reduction was reached with high-tapered with boat-tail and not with low-tapered with boat-tail. Since low-flat and low-tapered are not beneficial for the double floor potential either, these were not included in the three levels of aerodynamic measures. Lowest drag reduction was reached with high-flat with boat-tail (note: w/o boat tail is the reference case).

- Hybrid-on-demand (see chapter 4 and section 5.2.1.): the 80kW EMG combined with 20kWh battery is the tested variant (see chapter 3) and has the lowest saving potential. In the scope of this project, the
highest saving potential can be achieved with a large EMG (240 kW) to optimally harvest the braking energy in combination with a relatively light battery (10 kWh). As middle potential, an intermediate EMG sizing is chosen, since the EMG sizing dominates the potential, combined with the reference battery size.

Choosing three levels for each innovations also serves the assessment of combining of innovations in 5.3.4. This combined potential of all technologies was calculated (A+B, A+C, B+C and A+B+C) at low, middle and high potential for different mission profiles and fixed initial payloads of 8t, 15t and 25t. The results are further discussed in more detail in the sections below, in reverse order. In these sections, the most important evaluations results are shown and discussed. The complete evaluation results in tabular form can be found in Appendix B, following the above mentioned structure of low, middle and high potential including all possible combinations.

5.3.1 Potential of the HoD system (C)

The potential of the HoD system is shown in Figure 5.1 below for a fixed payload of 15 tonnes. The fuel saving potential is shown in terms of delta-KPI3 [ΔMJ/tonne*kilometres] for the three different HoD configurations low-, medium- and high-potential. This is directly proportional to litres of fuel reduced [Δ/litre*tonne*kilometres], since the model that was used already implicitly corrects for ΔSoC as it was calibrated to SoC-corrected simulations performed by ViF in the previous chapter.

A couple of observations can be made: first, the simulation results show strong variations depending on the cycle and especially the configuration setup. In all simulations, the least optimal hybrid configuration is the setup with the largest battery and smallest EMG (80 kW). This represents the current demonstration trailer as built and tested in this project. The simulation results show fuel savings in the order of 1-6%, depending on the mission profile: roughly 1% on a flat and hilly motorway, in comparison to 6% in an urban environment or on a motorway with steep hills. This is in line with the demonstration test results discussed in the chapters above: the urban test result match and the motorway test results fall in between the “hilly” and “steep hills” category, since the actual driven motorway during the tests indeed also falls in between these categories. For ease of comparison, the tested results for urban and motorway driving have been drawn into the figure.

The best performing system setup is the large EMG (240 kW) with a small battery. This is not surprising, since a large motor can regenerate more braking energy, as was also shown in the “simulation” chapter 4. The potential of the 160 kW and 20 kWh system lies somewhere in between these two configurations and are therefore classified as “middle” potential option. The HoD design with a 240 kW motor is very effective in
urban settings and steep hills, with savings percentages ranging up to 18-19%. Under bad conditions (flat, motorway) the savings potential of the 240 kW motor drops to maximally 4%. This is explained by the high velocities and low driving dynamics which limit the potential of regenerative braking.

Another interesting observation is the low impact of traffic conditions. On average, the impact low versus high congestion levels is no more than 1%. The reason for this lies in the available data that was considered for the mission profiles. The variation in driving dynamics between low, medium and high traffic show low variation. More data measured throughout a longer period of time could give more insights into the true variation of driving behaviour and acceleration. Statistical analysis of such data becomes crucial to compare congestion levels and the impact of those on the fuel consumption, especially for hybrid drivetrains with the capacity to recuperate braking energy. The measurement and analysis of such data is noted here as a recommendation.

The influence of payload is shown by error bars in figure 5.2 below for different mission profiles. Heavier vehicles are in general beneficial for the HoD configuration, especially when a large EMG (more regeneration potential) is considered. In this case, higher fuel savings can be achieved: see bottom error bar. Lower payloads will decrease the savings potential, see upper error bar. Variations in payload of ca. 10 tonnes can have an effect of up to 2% under urban driving conditions and steep hills. On the motorway, this effect is limited to 1%.

![Figure 5.2 Effect of payload on the configuration 240kW EMG /10kWh battery under various mission profiles](image)

5.3.2 Aerodynamic loss reduction due to advanced aerodynamics (B)

As expected, the aerodynamic measures are effective for motorway environments: fuel savings range from 0 to 6% per tonne*kilometres, in line with the results of the on-road tests in the “test results” chapter. Obviously in the urban context, aerodynamic measures are not effective at all, because of the low driving speeds. The extra weight of the aerodynamics innovation is a small penalty for the technology, especially at low velocities, where the share of the aerodynamic drag in the overall road load is reduced and replaced with inertial and rolling resistance forces that need to be overcome. The following can be concluded: Under the best conditions, the boat tail achieves fuel savings of roughly 2-3%. The same applies to the adaptable configurable roof. When combined, fuel savings of up to 7% can be achieved. This is in line with the DAF and VOLVO measurements (see previous chapters).

The fuel savings strongly depend on the mission profile of the vehicle. High driving dynamics increase the required inertial forces to overcome the road load, hence reducing savings potential of aerodynamics. The same applies to heavy loads, which increase the rolling resistance. Steep hills can be of influence to the technology when this results in lower driving speeds.
It needs to be pointed out again: The full potential of the aerodynamic trailer could not be measured or modelled in this project, since the reference trailer already included side skirts and the curved bulk head. If the aerodynamic TRANSFORMERS innovations were compared to the standard tractor-semitrailer configuration as found on the European roads at this moment, the savings potential would be much higher.

- Evaluation based on drag reduction data from measurements, for SCB semi-trailer
- Realistic routes, no constant speeds
- Highest impact on routes with highest average speed, no impact at low speeds (urban)
- Impact boat tail on FC: up to 2 to 3%
- Impact movable roof on FC: up to 2 to 3%
- Combined FC savings up to 6 to 7% in realistic routes

Note: reference included optimized bulkhead and sidewings → impact of all combined measures higher than shown here

Figure 5.3 Potential of aerodynamic measures

### 5.3.3 Loading efficiency increase due to double load floor (A)

Increasing the loading efficiency of the trailer can be a very effective measure, almost independent of the cycle that is driven. The decisive factor which determines the loading efficiency is the additional payload that can be carried in relation to the reference payload: At high payloads an additional tonne of loading has much lower impact on the savings than at low payloads.

**Potential of efficient loading**

- Additional floor space w/o double floor: +1 pallet → +3% fuel consumption saving per ton.km
- Impact double floor shows high potential, and is dependent of type of cargo: volume vs. mass
- Cargo density study shows that up to approx. 7 ton additional cargo is realistic
- In the evaluation, +1, +3 and +5 ton additional cargo scenario’s are used
- Example of averaged impact on fuel consumption using various road types and congestion levels, in %/ton.km:

<table>
<thead>
<tr>
<th>FC impact</th>
<th>Payload 8 tons</th>
<th>Payload 15 tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1 ton</td>
<td>-9 %/ton.km</td>
<td>-3 %/ton.km</td>
</tr>
<tr>
<td>+3 ton</td>
<td>-22 %/ton.km</td>
<td>-11 %/ton.km</td>
</tr>
<tr>
<td>+5 ton</td>
<td>-31 %/ton.km</td>
<td>-17 %/ton.km</td>
</tr>
</tbody>
</table>

Figure 5.4 Potential of efficient loading
5.3.4 Combined effects (A+B, A+C, B+C, A+B+C)

When combined, the TRANSFORMERS innovations can reach energy savings well beyond 25% per tonne*kilometres. The highest overall effect from TRANSFORMERS innovations with the current technology can be achieved on the motorway with steep hills. In this case, when considering a large HoD EMG (240 kW), a high tapered roof (incl. boat-tail) and efficient loading gain of 5t (on top of the initial 15t), the savings percentage of the technology can be 31%. Under similar conditions, the current demonstrator (80kW motor) can achieve savings in the range of 17%: 6% HoD / 2% aerodynamics / 9% loading efficiency.

5.4 Future potential of TRANSFORMER technologies

In order to investigate the future potential of TRANSFORMER technologies, new calculations were performed, for a detailed set of results: see Appendix B, Table B.2. For these calculations, the additional weight penalties of aerodynamic and hybrid measures were reduced. In the case of hybrid measures, the battery pack density was assumed to be 10kg/kWh, which is realistic for automotive applications instead of 30kg/kWh for the prototype demonstration battery pack. For aerodynamic measures, the previously considered weight penalty of 180kg was neglected for future potential. The additional weight of the double load floor was kept the same.

- **Potential of the HoD system (C)**
  For the optimal configuration (10kWh and 240 kW) with reduced battery weight, 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 relatively 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 TRANSFORMERS innovations at an average payload of 15t is equal to about 31%.

See section 4.5 for the future potential of the control strategy and plug-in functionality for the HoD system.

5.5 Conclusions

The question whether 25% savings can be achieved with the TRANSFORMERS innovations can be answered as follows:

- When combining all high potential TRANSFORMERS technologies more than 25% savings potential can achieved at nearly all mission profiles at average payload. At higher payload, the savings potential is lower and at lower payload, the savings potential is higher. On a flat surface on the motorway, the savings potential at a payload of 15t is only 24%. On all other routes, the potential is higher and up to 31%. It is noted here however, that these savings are only realistic under specific conditions: This implies a large HoD EMG and a small battery pack (240kW/10kWh), full use of the aerodynamic measures (high tapered + boat tail) and ideal product density for increased loading (Stonnes of extra payload due to loading efficiency).
- Under specific conditions (8tonnes initial payload), loading efficiency (+5 tonnes) has the highest potential and can achieve savings to the amount of 28-32%.
- HoD performs best in dynamic urban driving cycles and achieves with the current design roughly 5-6%. In future applications with larger dimensions up to 20% could be achieved.
- Aerodynamic measures contribute on the motorway to the overall savings with up to 7%.
6 Economic assessment of the TRANSFORMERS innovations

In this chapter, the economic potential of the TRANSFORMERS innovations is evaluated for a number of representative use cases. This assessment is done using the economic saving potential in these use cases. Since no cost data is available within the project out of confidentiality reasons, the assessment is limited to the economic saving potential, based on the impact on fuel consumption from the previous chapter. Note that the economic savings mentioned in this chapter do not equal the economic savings as shown in the result tables in appendix B, since mixed conditions instead of constant conditions were used in the economic assessment in this chapter. The evaluation has been done for the three different innovations separately, as well as when combined. After a description of the use cases and the assessment approach and assumptions in Sections 6.1 and 6.2, the results are given in the third and final section.

6.1 Definition of the use cases

Based on the analysis of European road freight transport (see Chapter 2) the choice is made to analyse the economic potential for short distance, long distance and urban transport of palletized goods.

6.1.1 Short distance international transport.

Together with Procter & Gamble and one of its carrier companies, GeoDis, two EU transport cases have been created. The cases consist of long distance truck missions covering roads in hilly terrain.

The first use case of P&G consists of a trip back and forth from a factory in Euskirchen (EUS, Germany) to a distribution centre in Amiens (LSA, France). In Figure 6.1, the average day trip composition is shown.

The top left figure shows the driving and resting times. It shows that the 315 km trip is driven back and forth twice a day. The bottom left figure shows that the Euskirchen-Amiens trip is fully loaded and the way back is partly empty. The middle left figure shows that the road consist of predominantly motorways in hilly terrain. This is translated to the S5 and S3 road types in the bottom right figure.

6.1.2 Long distance international transport.

The second case consists of a one-way trip from Euskirchen to Rome (Italy). The trip includes high elevation changes due to the crossing of the Alps. The composition of the trip can be seen in Figure 6.2.
The figure shows that the case consists of a one-way trip with a fully loaded vehicle from Euskirchen to Rome. The distribution in road types show that the route mostly consists of motorway but with a variation in elevation and congestion patterns.

### 6.1.3 Urban round trip

The urban round trip represents a route over mostly urban flat terrain in the Netherlands, representing urban distribution. Since multiple deliveries are made during the round trip, the payload of the vehicle decreases over the course of the route. The schematic figures of the round trip are shown in Figure 6.3. One roundtrip is 90 km (done 4 times a day), the map shows a section of the route in and around Amsterdam. A minor part of the roundtrip consists of a motorway part from and to the distribution centre. Furthermore, 10% of the driving time is in heavily congested conditions due to daily rush hour.
6.2 Assessment approach and assumptions

In this section the approach of calculation of the economic potential for the use-cases and the assumptions made for model parameters are described.

6.2.1 Assessment approach

The results shown in Appendix B are used as lookup-table for the economic assessment. The fuel consumption per kilometre (and tonne\*kilometres) is calculated for the default situation and for the different saving measures (individually as well as combined) under different conditions (payload / traffic / topology).

Each use case has been described as a daily schedule, stating per time period the activity of the driver and (if driving) the characteristics of the vehicle and the road that is driven. Table 6.1 shows an example of such a daily schedule where the driver is resting until 06:30 (start of his work day) and driving from 06:30 until 08:00. The driving time is divided in a hilly (S3) and a flat (S1) motorway part. The saving column shows that a version of the Hybrid on Demand measure is applied, in this example a 20 kWh battery and 80 kW EMG.

<table>
<thead>
<tr>
<th>From time</th>
<th>To time</th>
<th>Location</th>
<th>Activity</th>
<th>Profile</th>
<th>Payload</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>06:30</td>
<td>DC</td>
<td>resting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06:30</td>
<td>07:00</td>
<td>road</td>
<td>driving</td>
<td>S3_C003</td>
<td>25000</td>
<td>['BRK_20kWh_80kW']</td>
</tr>
<tr>
<td>07:00</td>
<td>08:00</td>
<td>road</td>
<td>driving</td>
<td>S1_C002</td>
<td>25000</td>
<td>['BRK_20kWh_80kW']</td>
</tr>
</tbody>
</table>

In the next step the daily schedule is extrapolated to show the driver and trip characteristics for each minute of the day. The resulting table is combined with the outputs of the model in order to estimate the fuel consumption per minute. By looking up the output with the same profile, payload, saving combination the fuel consumption per kilometre is added to the table. The fuel consumption per minute is found by multiplying the fuel consumption per kilometre with the average speed on the respective road profile (in km/min). The fuel costs are calculated by multiplying the total fuel consumption with the fuel price. The driving costs are calculated by counting all minutes where the activity status of the driver is ‘(un)loading’ and multiplying with the wage of the driver.

The total costs are finally divided by the kilometres driven per day to get an average cost per kilometre. This costs per kilometre are multiplied by the average yearly mileage. The net present value (NPV) is calculated for each technology separately.

6.2.2 Assumed parameters

Table 6.2 shows the input parameters that have been used in order to calculate the economic potential. The diesel price is used to monetize the fuel consumption. The driver costs are only used to estimate the costs of increased loading times. The actual driving time is assumed to be unaffected by the measures and is therefore left out of the analysis.

The economic potential of the technologies was evaluated using the net present value (NPV) of the cumulated annual savings. For this purpose, the interest rate is assumed to be 4\% and the lifetime of the technology is assumed to be 8 years. The justification of this assumed technology lifetime goes beyond the scope of this economic assessment. In brief, the assumption is based on the average lifetime of a truck (8 years) and the expected return of investment (ROI) for an end-user if the money is invested elsewhere (e.g. in banking). The NPV provides an indication for the potential investment costs of a technology in order to break even after a selected period of time at a given interest rate. For example, at an interest rate of 4\%, a technology lifetime of 8 years and an savings rate of 1.232 €, the NPV is 10.000€. Inversely, it can be stated that in order to amortize the investment costs of 10.000€ for a technology – money which in general needs to be borrowed from and paid back to a bank - over a period of 8 years at a fixed interest rate of 4\%, it requires at least an annual income (or savings) of 1.232 €.

The additional loading time on the beginning and end of each trip is roughly 10 minutes, corresponding to the graphs in section 3.3.2 and the assumption that 10-15 extra pallets can be transported with the use of the double load floor.
Table 6.2 Parameters used

<table>
<thead>
<tr>
<th>Parameters used</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel price, ex VAT</td>
<td>1 [€/litre]</td>
</tr>
<tr>
<td>Driver costs, ex VAT</td>
<td>50 [€/hour]</td>
</tr>
<tr>
<td>Technology lifetime</td>
<td>8 [years]</td>
</tr>
<tr>
<td>Interest rate</td>
<td>4 [%]</td>
</tr>
<tr>
<td>(un-)loading time</td>
<td>10 [minutes]</td>
</tr>
</tbody>
</table>

6.2.3 Technology scenarios

For each of the three technologies, three scenarios are analysed, a low, middle and high potential scenario. The scenarios are described in the previous chapter. For the combination of measures, the average loading potential is combined with high potential aerodynamics and HoD measures. The choice for the average loading potential is made because this is thought to be the most likely additional payload that can be transported with the additional loading floor. In contrast to the other two technologies the potential is not determined by the technological state but by characteristics of the load.

6.3 Assessment results

First, the results of individual measures on the use cases are given. Then, the effects of combining different measures are included.

6.3.1 Results of individual measures

In this section the economic assessment results are given and analysed for individual measures, i.e. loading efficiency, aerodynamic efficiency and hybrid on demand. In order to show the effect of yearly mileage, the economic potential is calculated for 100,000 and 200,000 kilometres per year, the latter being on the high end of the realistic range. Note that the economic savings scale with the yearly mileage, so the savings of any mileage can be calculated easily.

6.3.1.1 Short distance international transport – individual measures.

In Table 6.3, the results of the economic potential analysis for increased loading efficiency for the Amiens case is given. The tables shows that all scenarios decrease the fuel costs per tonne*kilometres. However, due to the increased loading time, only the middle and high scenario account for a positive economic potential.

Table 6.3 Short distance international transport, loading efficiency economic potential

<table>
<thead>
<tr>
<th>Ref.</th>
<th>FC impact [/ton.km]</th>
<th>100 000 km</th>
<th>200 000 km</th>
<th>100 000 km</th>
<th>NPV [€]</th>
<th>Total annual savings [€/yr]</th>
<th>NPV [€]</th>
<th>Total annual savings [€/yr]</th>
<th>NPV [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading +1 tonne</td>
<td>-3%</td>
<td>€ -3,262.03</td>
<td>€ -21,962.41</td>
<td>€ -6,524.06</td>
<td>€ -43,924.81</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading +3 tonne</td>
<td>-12%</td>
<td>€ 381.44</td>
<td>€ 2,568.11</td>
<td>€ 762.87</td>
<td>€ 5,136.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading +5 tonne</td>
<td>-19%</td>
<td>€ 3,240.00</td>
<td>€ 21,814.12</td>
<td>€ 6,480.01</td>
<td>€ 43,628.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4 shows the results for aerodynamic measurements. The table shows that all three scenarios account for fuel reduction of 2-4% for the Amiens case. The lower savings is due to a heavily congested section [=lower speed] on the road due to roadworks. The high flat with boat tail and high tapered without boat tail show similar savings of ~900 euros per year while the high tapered boat tail performs a lot better with savings of >1500 euros per year.
Table 6.4 Short distance international transport, aerodynamics economic potential

| Ref.       | FC impact [/ton.km] | 100 000 km |  | 200 000 km |  |  
|------------|---------------------|------------|------|------------|------|------|------|------|------|
|            |                     | Total annual savings [€/yr] | NPV [€] | Total annual savings [€/yr] | NPV [€] |  
| AERO HF BT | -3%                 | € 902.82   | € 6,078.47 | € 1,805.64 | € 12,156.93 |  
| AERO HT NBT| -2%                 | € 851.64   | € 5,733.86 | € 1,703.27 | € 11,467.71 |  
| AERO HT BT | -4%                 | € 1,565.13 | € 10,537.60| € 3,130.25 | € 21,075.20 |  

Table 6.5 shows that all hybrid on demand variations show a positive economic potential for the Amiens case. Depending on the scenario and the yearly mileage, the net present value of the technology over 8 years of time is between 2700 and 20000 euros.

Table 6.5 Short distance international transport, hybrid on demand economic potential

| Ref.             | FC impact [tonne*km] | 100 000 km |  | 200 000 km |  | NPV [€] | NPV [€] |  
|------------------|----------------------|------------|------|------------|------|------|------|------|
| Hybrid 20-80     | -1%                  | € 408.40   | € 2,749.66 | € 816.80  | € 5,499.32 |  
| Hybrid 20-160    | -3%                  | € 969.34   | € 6,526.33 | € 1,938.68| € 13,052.66 |  
| Hybrid 10-240    | -4%                  | € 1,485.01 | € 9,998.22 | € 2,970.03| € 19,996.45 |  

6.3.1.2 Long distance international transport – individual measures

Table 6.6 shows that loading efficiency potentially decreases full consumption per tonne*kilometres up to 10%. All scenarios show a fuel reduction but only the middle and high potential scenario show a positive economic potential because of increased loading times.

Table 6.6 Long distance international transport, loading efficiency economic potential

| Ref.             | FC impact [tonne*km] | 100 000 km |  | 200 000 km |  | NPV [€] | NPV [€] |  
|------------------|----------------------|------------|------|------------|------|------|------|------|
| Loading +1 tonne | -1%                  | € -827.44  | € -5,570.95| € -1,654.88| € -11,141.89|  
| Loading +3 tonne | -6%                  | € 1,341.40 | € 9,031.31 | € 2,682.80 | € 18,062.62 |  
| Loading +5 tonne | -10%                 | € 3,186.57 | € 21,454.33| € 6,373.13 | € 42,908.66  

In Table 7 the results for aerodynamic measurement on long distance international transport are shown. As for the short distance international transport, the low and middle potential scenarios show similar savings while the high potential scenario adds up to almost twice this figure.
Table 6.7 Long distance international transport, aerodynamics economic potential

<table>
<thead>
<tr>
<th>Ref.</th>
<th>FC impact [/tonne*kilometres]</th>
<th>100 000 km</th>
<th>200 000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total annual savings [€/yr]</td>
<td>NPV [€]</td>
<td>Total annual savings [€/yr]</td>
</tr>
<tr>
<td>AERO</td>
<td>-2%</td>
<td>€ 744.76</td>
<td>€ 5,014.31</td>
</tr>
<tr>
<td>HT BT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AERO</td>
<td>-2%</td>
<td>€ 701.24</td>
<td>€ 4,721.25</td>
</tr>
<tr>
<td>HT NBT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AERO</td>
<td>-3%</td>
<td>€ 1,308.17</td>
<td>€ 8,807.56</td>
</tr>
<tr>
<td>HT BT</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the international long distance use case, usage of the HoD technology potentially accounts for 2-6 % fuel savings, depending on the motor and battery size as can be seen in Table 6.8.

Table 6.8 Long distance international transport, hybrid on demand economic potential

<table>
<thead>
<tr>
<th>Ref.</th>
<th>FC impact [/tonne*kilometres]</th>
<th>100 000 km</th>
<th>200 000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total annual savings [€/yr]</td>
<td>NPV [€]</td>
<td>Total annual savings [€/yr]</td>
</tr>
<tr>
<td>Hybrid 20-80</td>
<td>-2%</td>
<td>€ 759.53</td>
<td>€ 5,113.74</td>
</tr>
<tr>
<td>Hybrid 20-160</td>
<td>-4%</td>
<td>€ 1,696.91</td>
<td>€ 11,424.87</td>
</tr>
<tr>
<td>Hybrid 10-240</td>
<td>-6%</td>
<td>€ 2,546.49</td>
<td>€ 17,144.86</td>
</tr>
</tbody>
</table>

6.3.1.3 Urban roundtrip – Individual measures

Table 6.9 shows that increased loading efficiency has a negative economic potential for the urban roundtrip case, although fuel consumption per tonne*kilometre is decreased. Due to the short trips and the decreasing payload during the trips the fuel savings are not high enough to compensate for the increased loading time.

Table 6.9 Urban distribution, loading efficiency economic potential

<table>
<thead>
<tr>
<th>Ref.</th>
<th>FC impact [/tonne*kilometres]</th>
<th>50 000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total annual savings [€/yr]</td>
<td>NPV [€]</td>
</tr>
<tr>
<td>Loading +1 tonne</td>
<td>-1%</td>
<td>€ - 6,126.27</td>
</tr>
<tr>
<td>Loading +3 tonne</td>
<td>-9%</td>
<td>€ - 3,383.78</td>
</tr>
<tr>
<td>Loading +5 tonne</td>
<td>-14%</td>
<td>€ - 1,234.65</td>
</tr>
</tbody>
</table>

The result in previous chapter have shown that aerodynamic measures have little effect in urban surroundings. This is reflected by the neglectable results of the economic potential analysis as shown in Table 6.10.
In contrast to the aerodynamic measures, the Hybrid on Demand measures prove to work especially well in urban conditions. This is reflected by the positive economic potential for all scenarios, as shown in Table 6.11.

**Table 6.11 Urban distribution, hybrid on demand economic potential**

<table>
<thead>
<tr>
<th>Ref.</th>
<th>FC Impact [/ton.km]</th>
<th>50 000 km</th>
<th>NPV [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td>-5%</td>
<td>€ 1,268.34</td>
<td>€ 8,539.38</td>
</tr>
<tr>
<td>20-80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>-11%</td>
<td>€ 2,889.74</td>
<td>€ 19,455.85</td>
</tr>
<tr>
<td>20-160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>-17%</td>
<td>€ 4,446.11</td>
<td>€ 29,934.49</td>
</tr>
<tr>
<td>10-240</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.3.2 Combinations of measures

In order to make an assumption of the total potential of TRANSFORMERS measures, the economic potential is also calculated for the combination of all three technologies. The results are shown in Table 6.12. Combination of all measures accounts for fuel savings of 15-24% depending on the use case. These savings are slightly lower than the savings presented in the previous chapter, since here the assessment is done for mixed conditions instead of constant conditions.

The total annual savings and NPV show that the economic potential is maximized as well by combining measures for the international transport cases. For the urban retail case, the increased fuel efficiency is insufficient to account for the increased loading time and the resulting economic potential for combined measures is thus worse than the individual Hybrid on demand cases.

**Table 6.12 Economic assessment results for combined measures**

<table>
<thead>
<tr>
<th>Campaign</th>
<th>FC impact [/tonne*kilometres]</th>
<th>100 000 km</th>
<th></th>
<th>200 000 km</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total annual savings [€/yr]</td>
<td>NPV [€]</td>
<td>Total annual savings [€/yr]</td>
<td>NPV [€]</td>
<td></td>
</tr>
<tr>
<td>EU long distance</td>
<td>-15%</td>
<td>€ 5,093.34</td>
<td>€ 10,186.69</td>
<td>€ 68,584.37</td>
<td></td>
</tr>
<tr>
<td>EU short distance</td>
<td>-20%</td>
<td>€ 3,292.12</td>
<td>€ 6,584.23</td>
<td>€ 44,329.97</td>
<td></td>
</tr>
<tr>
<td>National urban</td>
<td>-24%</td>
<td>€ 591.32</td>
<td>€ 3,981.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.4 Conclusions

The economic potential 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 TRANSFORMERS technologies under real-life operation. Whether or not this leads to a valid business case depends on the technology costs. In general, it can be concluded that the economic savings and NPV’s calculated show the potential for a viable business case in future.

- For aerodynamic measures, under the best considered use case, the NPV is up to 21000 €. Conditions: short distance international transport, 200000 km per year. This savings is valid for the high-tapered roof and the boat tail.
- For the HoD, under the best considered use case, the NPV is up to 34000 €. This is valid for the largest configuration (240kW/10kWh) and taking into account long distance international transport, 200000 km per year.
- The highest NPV for loading efficiency is 43000 €. This is the case for long and short distance international transport, where loading and unloading locations are far away from each other, and for 200000 km. For the urban round trip, the NPVs are negative. This means, since the loading and unloading locations are so close to each other in this scenario, the fuel savings to not weigh up against the additional driver/warehouse 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 up to roughly 70000 €. In this case, all technologies profit from the large amount of annual mileage (200000 km) 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.
7 Roads towards implementation

The developed and demonstrated TRANSFORMERS innovations have shown their benefit in real world applications, however, are not yet ready for large scale production. Chapter 7 explores the required roads towards this implementation of the innovations, discussing recommendations for technical improvements and paths towards exploitation. This chapter also includes project specific lessons learned and ends with an extensive discussion of the compatibility of the innovation characteristics with the VECTO tool, to be used in the near future for the assessment of the CO₂ impact of heavy-duty vehicles in certification procedures.

7.1 Recommendations for technical improvements

In this report, in particular in Chapter 5 and Chapter 6, it has been shown that the TRANSFORMERS innovations have the potential to result in a positive business case for a relevant set of typical use cases.

At the same point it is important to point out that the demonstrator versions of these innovations were prototypes that were designed and constructed to prove the feasibility of an idea for the duration of the project.

Before introducing them into the market it is important to realize that further technical development is needed aiming at:

• demonstrating an acceptable durability of these solutions in different applications, driving conditions and situations (i.e. in further field testing)
• optimising performance of the system
• decreasing the complexity of these solutions
• reducing the weight of these add-on systems
• 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 these innovations. This is important, because in the beginning, production numbers will be limited and the correspondingly high per unit costs for development and production could exceed the anticipated profits that were estimated in Chapter 6.

In the following paragraphs some specific recommendations for further technology development for each of the innovations is treated separately.

7.1.1 Aerodynamic improvements because of the configurable roof

• This section focuses on the configurable roof that allows the reconfiguration of the outer shape of the trailer.
• It is important the roof position is as easy as possible to select and operate. In the demonstrator vehicle this is currently done by the driver. The driver should not have too many choices – the concept should be very easy to understand and or automated as far as possible.
• With the availability of sensors that measure the volume and weight of the payload, there is scope for further driver assistance.
• There is a clear scope for weight reduction of the configurable roof construction that needs to be further investigated.
• To maximise the transport missions as much as possible where the configurable roof can be utilized, the logistic planning software should take this into account. The driver should also use the technology when picking up different loads on the spot market during a mission. In the best case the software knows that the highest cargo shall be placed at the front. To the back the cargo height needs to decrease to be able to set the roof in a tapered position.
• In principle, with payload sensors, the reconfiguration could be fully automated and faster than a manually operated solution. Although being cheaper with the same functionality, the manually operated solution needs more time for the reconfiguration process and training. As a further step in automation it would be conceivable that control takes place from the truck cabin (if communication between tractor and trailer would allow for this) or from the loading dock.
7.1.2 Load optimization measures

- The real potential of the double floor can be made more clear when pallet heights or transported volumes are also registered.
- Also the implementation of load sensors will be an enabling technology that would, in addition help in mixing different type of pallets in one shipment.
- The extra weight of the flexible floor can/needs to be reduced.
- To maximise the transport missions as much as possible where the flexible floor can be utilised, the logistic planning software should take this into account. The technology should also consider picking up different loads during a mission.
- The load-volume-indicator was developed and tested in the project. As it turned out, the tractor/trailer implementation is still a big challenge, because of the high number of different tractor/trailer combinations and affiliated hardware and software interfaces. Currently no standard protocol exists to implement the LVI into a tractor/trailer combination.

7.1.3 Hybrid on Demand powertrain

- At this moment the costs of the hybrid system components (in particular of the battery) are very high, in part due to special prototype components. To minimize costs, efforts should be made to make maximum use of components that are already serially produced for other applications.
- The system should be easy to use. The semi-trailer should be able to work with every towing vehicle with minimal modifications.
- The highest efficiency of the system can be reached if a standardized interface between tractor and semi-trailer is introduced. An international standard for communication between tractor and semi-trailer should be proposed by the follow-on AEROFLEX project.
- The demonstrated “Hybrid-on-Demand” (HoD) control system linking the tractor and semi-trailer was a first choice. With more advanced control systems offering complete vehicle energy management it is expected to significantly improve the potential efficiency of the HoD system.
- At the same time, the hybrid technology is being continuously further developed (different battery technologies, EMG, voltage levels etc...). The HoD innovation development should anticipate on this. In that respect it is worthwhile mentioning the plug-in option that was mentioned in Chapter 4. With this approach extended zero-emissions range e.g. in city centres (with low noise requirements) becomes feasible. This could also be interesting for temperature controlled transports which could use the HoD for auxiliary power and plug in during rest periods.
- There is a clear scope to further reduce the weight of the demo HoD solution (dedicated axles, weight reduction of the battery encapsulation,...).
- Deliverable report 2.4 and section 4.5 shows that there is still a high potential for improvements using different HoD control strategies for different routes. The strategy should also consider the 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, depending on the type of route the vehicle is driving. A strategy like predictive energy management systems can take road and traffic conditions into account and are able to optimize fuel and energy savings. This approach may enable the full potential of HoD in typical road based haulage applications.

All of the above mentioned recommendations for further technology development are technologically quite feasible and do not require a lot of additional development. They will however only take place when there is a concerted effort to reduce the time to market for these innovations. The next paragraph identifies the actions taken and being envisaged to realize this.

7.2 Paths towards exploitation

There is significant potential to exploit the results from the TRANSFORMERS project: several of the TRANSFORMERS innovations are applicable both to the existing vehicle fleet as well as to newly built vehicles. Identifying the paths towards exploitation strategy based upon a thorough evaluation and sound business case, will strengthen and speed up the market uptake of successful results from the project.

Of course the paths towards exploitation will vary between the industry and research partners, and will also vary whether the results can be considered to be public or commercially exploitable.

For the industry partners the ultimate goal is to strengthen their positions in their respective markets by developing the individual TRANSFORMERS technologies into innovative commercial products and services. In this respect the knowhow gained in the TRANSFORMERS project is an enabler for future research, advanced
engineering and product development projects in the context of distributed hybrid drivelines, advanced aerodynamics, and load optimization. The TRANSFORMERS innovations are then expected to be introduced either individually or jointly as niche market solutions. To move forward the exploitation of the innovations a number of activities have been identified:

1. **Tackling** of the technological improvements and challenges identified in Section 7.1

2. **Investigation of the business case by the trailer manufacturers who might bring a technology to the market**. As far as the HoD system is concerned, such investigation would depend on the availability of (expected) costs for battery, EMG, gearbox. With this data, and the test and simulation results of TRANSFORMERS (and of course their internal knowledge about the market, e.g. acceptable time for ROI) they could make such investigations.

3. **Societal issues, working towards removing obstacles/limitations with standardization and legislation towards implementation of these innovations**. This would include for example to review safety regulations to enable these new technologies.

   In the TRANSFORMERS project it was further noticed on a number of occasions that the implementation of these innovations is hindered by existing standards and limitations on vehicle weight, size, braking strategies, tractor-trailer communication, certification procedures, etc. In this respect, a study of necessary changes to standardization is an intricate part of the move towards the market of these technologies. For distributed drivelines in particular, it is necessary to develop and implement an international standard so that control of a HoD system can be provided between different brands of tractors and different brands of trailers. The HoD pre-standardisation tractor-trailer communication “framework” developed within TRANSFORMERS forms the basis of such a potential future standard. This framework is applicable to both wired and wireless communication systems between the tractor and trailer, and as such is to some extent future proofed. The next steps including presentation of these results and proposals to national mirror groups of appropriate ISO committees will likely be taken by a follow-on project, i.e. AEROFLEX.

   Finally it should be mentioned that legislation could also boost the implementation of these innovations. Future CO₂ regulation might drive efficiency improvements where such investments will pay off also in the wider transport market. The possible changes needed to the current regulations is treated in Section 7.4. All of this is covered in the follow-on H2020 AEROFLEX project.

4. **Widening the application range of the TRANSFORMERS innovations**. In this project the focus was on improving transportation with tractor/semi-trailer combinations. And based on the present results it seems that for these vehicles the HoD innovation would be best usable in transport routes with frequent and significant elevation changes and transport in municipal areas with a lot of braking and acceleration. Aerodynamic innovations on the other hand give highest potential in high traveling speed applications (long distance haulage transport on motorways).

   Of course, with a wider application range, also the willingness to further invest in these innovations increases. For this reason it is important to consider other vehicle combinations than the tractor and semi-trailer, such as the standard road train (truck-trailer combination of maximum 18.75m) and the European Modular System combinations with a truck, dolly and semi-trailer. The efficiency improvements should be flexible and usable in many configurations. This is one of the topics for investigation by the follow-on AEROFLEX project.

5. **Leading by example**. For the TRANSFORMERS technologies to be introduced in the market, one or several actors would possibly take the lead to develop an offer. This could be by a consortium of shippers, truck OEMs and trailer manufacturers. Together they could set up a scheme that would reduce the risk of fleet operators to invest in these technologies. Such a pilot could aim at those use cases with highest profit margin.

All of the above activities focus on strengthening the case for the implementation of the TRANSFORMERS technologies and can be performed by the existing consortium partners. It is, however, essential that other organizations and companies should be made aware and interested in cooperating in the further development and implementation of these innovations. That is why it is important to continue efforts to disseminate the results of the TRANSFORMERS project. Such dissemination activities, are already being undertaken and are straightforward considering the facts that:

- Most partners are directly or indirectly members of ERTRAC (European Road Transport Research Advisory Council) which is recognized and supported by the European Commission
Volvo and DAF are members of EUCAR, the European Council for Automotive R&D, in which all major European vehicle manufacturers are involved, and are also members of ACEA (European Automobile Manufacturers Association).

Bosch is a member of CLEPA, the European Association of Automotive Suppliers.

Fraunhofer Gesellschaft, IFSTTAR, TNO and ViF are members of EARTO (European Association of Research and Technology Organizations).

AIT (FEHRL 3rd party), Fraunhofer LBF, TNO and ViF are members of EARPA (Association of Automotive R&D Organizations).

ViF is a member of ARTEMIS Industry Association (Advanced Research & Technology for Embedded Intelligence and Systems).

IRU (International Road Transport Union) is global road transport organization, which upholds the interests of bus, coach, taxi and truck operators to ensure economic growth and prosperity via the sustainable mobility of people and goods by road worldwide.

Further, many consortium partners have working contact with governmental organizations at national and European level.

In particular it must be made clear in communication with fleet owners under which conditions these new technologies have a positive return on investment. Possibly dedicated (on-line) tools need to be developed for this purpose.

Current TRANSFORMERS dissemination measures will be reported in a separate publishable report.

Of course in the above activities all of the consortium partners could contribute. There are also paths towards exploitation that are unique to the research partners of the TRANSFORMERS project. These organizations typically want to strengthen their position in the respective field of research by making the individual expertise and knowhow visible in the research community (publications in specific journals and international conferences). The knowhow gained in the TRANSFORMERS project is an enabler for future research, consulting and advanced engineering projects in the context of distributed hybrid drivelines, advanced aerodynamics, and load optimization. The major technical project results will be considered for intellectual property application with the intention to license the respective technology. Within the project, students are educated (e.g. internships and master thesis) which strengthens the cooperation and knowledge transfer with universities.

7.3 Project-execution specific lessons learned

In summary for the project, the following lessons can be taken away:

Overall:

- The scope of the project was quite generic and could have been extended to many different vehicle configurations. Because of the limited time for the project it has been necessary to limit the research and especially the demonstration activities to the tractor/semi-trailer configuration. Overall, the project considers that vehicle technology for truck applications and its testing should consider the full vehicle combination, including the tractor unit, semi-trailer and trailer. The manner in which the project was executed could however be applied also to these other vehicle configurations.
- It has been demonstrated that a combination of testing and modelling (to a large extent in parallel) can yield greater insights into technology potential; at the same time, in the project, the limits for parallel modeling/testing/validation were tested. In future projects, phasing of these activities should show some more margin to ensure the necessary time for validation of the output.
- Adequate time should be allowed in project durations to allow for contingencies linked to prototype procurement, and testing especially when carried out on the public road.
- Data confidentiality laws limit accessibility of results from related projects.

On simulations:

- The DOW should be written a bit more specific. Instead of a general statement that models or data will be provided by the partners, it would be good to clarify who will deliver what.
- If simulation work is depending on real measurements, an extra amount of time should be included to compensate delays during testing (e.g. because of bad weather conditions).
7.4 Assessing the CO₂ impact using VECTO

Recently, the proposal [3] by the EC for the certification and determination of the CO₂ emissions of heavy-duty vehicles has been adopted. The determination of the CO₂ emissions will be done by a simulation tool called VECTO. The certification will start in 2019 for vehicles categories 4,5 9 and 10 including 4x2 and 6x2 tractor semi-trailer combinations, which are relevant for the TRANSFORMERS technology.

It is important for VECTO to accurately represent the benefits provided by vehicle measures presented in TRANSFORMERS, as it should provide the right incentives for fleet owners in terms of reduction of fuel consumption and CO₂ emissions to invest in energy efficiency measures. Attributing a CO₂ emission and fuel consumption value to a HDV gives customers insight into the relative fuel efficiency performance of different HDVs if the CO₂ value is accurately represented. The CO₂ certification using VECTO (Vehicle Energy Consumption Calculation Tool) [4] will also enable the monitoring and reporting of CO₂ emissions of heavy-duty vehicles registered in the EU. In addition, the European Commission is currently investigating the options for introducing CO₂ limitations (or labels) for HDV, the exact details currently not being decided.

The proposed certification and determination of the CO₂ emissions of HDV with VECTO only aims at standard vehicle configurations with conventional combustion engine only powertrains. This means that emissions and fuel consumption will be simulated, certified and reported for vehicles with standard type and size of body work, and trailers with a few standard technologies. For the formal certification, VECTO only simulates those standard configurations and therefore certain innovations, such as the ones developed in the TRANSFORMERS project, would not yet be incentivized because special trailers are not part of the certification.

Aside from whether or not technologies are included in the certification, the VECTO tool itself can be analysed as to if and how the tool needs to be adapted to be capable of simulating CO₂ emissions of innovative technologies such as TRANSFORMERS. Therefore, the gaps have been identified between the current technical functionality of the VECTO tool and the functionality needed to represent the TRANSFORMERS vehicle measures. This provide a guideline for possible further development of the VECTO tool, such that the outcomes of the tool can provide insight into the effectiveness of advanced vehicle energy efficiency measures proposed in the TRANSFORMERS project and other similar projects.

The characteristics of the TRANSFORMERS concept that have an influence on CO₂ emissions and that should be taken into account for the accurate simulation of the CO₂ emissions in the VECTO tool are:

a) The aerodynamic measures that influence the air drag \((C_d*A)\). These are the bulkhead, the side wings, the boat tail and the configurable roof.
b) Loading efficiency: the **adjustable double deck cargo area** feature comes with more floor surface (m²) and in some cases allows more goods to be loaded. Hence it could affect the CO₂ emissions per tonne×kilometres and per m³-km.

c) The **Hybrid on Demand system** is able to recuperate braking energy and use it to assist the propulsion of the whole vehicle (tractor semi-trailer combination) and thus affects the CO₂ emission, depending on the driving cycle.

d) Weight: the **construction of the bodywork and the HoD system** bring about a change in trailer mass which should be accounted for.

In the next section, the ability of VECTO to accurately represent the transport efficiency gains resulting from the aerodynamic measures, hybrid-on-demand trailers and loading efficiency measures developed in the TRANSFORMERS project are discussed.

### 7.4.1 Aerodynamic measures

**TRANSFORMERS** technologies: Aerodynamic curved front bulkhead, side skirts, boat tail, configurable trailer roof.

The aim of these technologies is to reduce the aerodynamic drag of a HDV. A lower aerodynamic drag reduces the driving resistance which is the dominant resistance factor of a HDV running at cruise speed. The achievable effect of these technologies on air drag can be quantified using the constant-speed test which is defined for the CO₂ certification of HDV in Annex VI in the current proposals. The test is to be performed with a HDV on a test track. Air drag is determined at two constant speeds by measuring torque at the hubs of the wheels of the driven axle. The actual air drag is corrected for possible cross wind to an air drag that represents the drag at zero crosswind. The test, however, is meant to determine the aerodynamic drag (Cd*A (0)) of a HDV with standard bodywork or a standard semi-trailer. For a tractor semi-trailer this means that for the test trailer a fixed mass and dimensions are prescribed. The baseline is standard trailer ‘ST1’, a 3-axle semi-trailer. The currently prescribed constant speed test would be suitable to determine the achievable effect of the air drag reducing technologies.

The EC considers to include the determination of air drag for alternative bodywork configurations in the future. The timeline is not clear yet. A proposed option to determine the air drag of alternative bodywork by the International association of the Body and Trailer Building Industry (CLCCR), is the use of a standardized, certified CFD calculation method, because this is considered a cheaper alternative to actual air drag measurements like the constant speed test. Such a method would be used to calculate the difference in Cd values between different body types. This would decrease the burden of constant-speed testing, which could be significant for small truck/trailer-body builders.

In the current certification procedure active aerodynamic devices are only allowed if it can be demonstrated that the device is always activated and effective to reduce the air drag at vehicle speed over 60 km/h. For the configurable-roof trailer the actual average CO₂ reduction depends on the usage of the trailer, because it depends on the type of cargo, the amount of cargo and how the cargo is stowed how often and how much the trailer roof can actually be lowered or tapered. For technologies that are only partly active in real world operation a utilization factor could be determined to calculate the average CO₂ emission level. For a consumer separate values for all settings will be helpful so that he can calculate for his own situation the achievable reduction potential. The utility factor should be based on extensive monitoring of the usage of the technology.

**Example:** Average CO₂ = CO₂tapered × 70% + CO₂non tapered × 30%

### 7.4.2 Loading efficiency measures

**TRANSFORMERS** technology: height adjustable double deck cargo area

This technology could allow a more efficient use of the available cargo volume as it doubles the floor surface. This has the potential to decrease the CO₂ emission per tonne and per m³ of the cargo transported.

VECTO calculates the distance specific CO₂ emissions for two payload situations, 1) empty and 2) a fixed value per vehicle category that approximates about 70% of the maximum payload. In addition to the g/km CO₂ emission, the tonne-specific and volume-specific CO₂ emissions are calculated. The tonne-specific emission is calculated taking account of the two prescribed payloads. The volume specific emission is calculated taking account of the theoretically usable (maximum) volume of the cargo area (but does not play a role yet in the certification/assessment).
Loading efficiency measures could be accounted for through a higher payload. This would increase the \( \text{CO}_2 \) emission in g/km but would reduce the \( \text{CO}_2 \) emission per tonne∙km of goods. Just like the tapered roof the actual average \( \text{CO}_2 \) reduction depends on the use of the trailer. There will be a difference between theoretical load capacity and actual real-world practice. To accurately reflect transport efficiency gains from loading measures, monitoring of actual in-use cargo loading is required.

7.4.3 Hybrid on Demand (HoD) trailer

TRANSFORMERS technology: a system of an electric motor-generator, mounted to one of the trailer axles, and a battery to enable the recuperation of braking energy. This energy is used to assist the propulsion of the whole vehicle (tractor semi-trailer combination), reducing the fuel consumption of the vehicle as a whole.

Electrified powertrains are currently not included in VECTO. An addition to VECTO has been considered that adds the capability to assess heavy duty hybrid vehicles, as described in [5] This type of extension to VECTO is needed to allow proper assessment of the energy efficiency performance of heavy duty hybrid vehicles, including the distributed drivelines such as formed by a conventional tractor in combination with a trailer with a Hybrid on Demand system and other configurations.

7.4.4 Weight

The TRANSFORMERS technology comes with a change in weight of the semi-trailer; aerodynamic additions, the HoD system and the double loading floor add weight to the trailer. The current VECTO instrument uses a default mass for the standard semi-trailer body configuration ST1 of 7500 kg. The VECTO tool could be adapted easily to allow a different input for the empty mass of a semi-trailer.

7.4.5 Conclusions

The current proposed legislative framework for the certification and determination of a \( \text{CO}_2 \) value with VECTO does not allow the accurate representation of the \( \text{CO}_2 \) reduction measures of the TRANSFORMERS concept because currently only the simulation of vehicles with non-hybrid powertrains and standard truck/(semi)-trailer bodywork is foreseen. The VECTO tool itself, however, is designed to simulate \( \text{CO}_2 \) emissions based on physical and measured properties of a whole HDV. This means that the technical basis of the tool is suitable to simulate the achievable \( \text{CO}_2 \) emissions of innovative concepts that reduce driving resistances. Therefore, maximum achievable impacts of air drag and mass can be accounted for quite easily.

Some innovations that reduce \( \text{CO}_2 \) emissions may not be utilized all of the time. For the TRANSFORMERS concept the trailer roof may only be lowered if cargo allows it. The same accounts for the double deck feature. This is only beneficial when more cargo can be stowed than would have been in a baseline situation with a single deck trailer. This means that to determine the average \( \text{CO}_2 \) emission a certain utilization rate needs to be taken into account. The actual utilization rate may strongly depend on individual conditions. Reporting of separate \( \text{CO}_2 \) emission values would allow a fleet manager to take into account his own estimate of the utilization rate.

Hybridization may be harder to integrate. In theory different approaches are possible for which complexity increases when more accuracy is required. Development times could become significant (years) for the more complex approaches, such as Hardware In the Loop Simulation (HILS) of the heavy-duty hybrid (HDH) system.

The conclusions are summarized in table 7.1 below.
<table>
<thead>
<tr>
<th>Transformer measure</th>
<th>Can the measure be simulated according current certification proposal?</th>
<th>What needs to be adapted?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic improvements</td>
<td>No, only standard bodywork and trailers allowed</td>
<td>The constant speed test can be used to determine ( C_{dxA} ) of the vehicle with innovative trailer concept. Alternatively, a certified calculation method can be used to determine ( C_d ) values. Requires a utilization rate when the measure is not 100% active.</td>
</tr>
<tr>
<td>Loading efficiency</td>
<td>No, only fixed payload and cargo volume</td>
<td>Requires allowance of a different payload input and a utilization rate when the measure is not 100% active.</td>
</tr>
<tr>
<td>HoD</td>
<td>No</td>
<td>Requires development of a hybrid VECTO add-on. Complexity and development time can be significant, depending on required modelling accuracy.</td>
</tr>
<tr>
<td>Weight</td>
<td>No, only standard bodywork and trailers</td>
<td>Add an input field for an alternative mass of the trailer.</td>
</tr>
</tbody>
</table>
8 Conclusions

This deliverable focused on analysing the results of testing, and various levels of simulation analysis to study the potential of the innovative measures within TRANSFORMERS. A number of different analyses were constructed so as to provide a comprehensive view of the sensitivities of energy use reduction per tonne*kilometres.

To demonstrate the technology, the partners have worked together to realizing two demonstrators. In turn these allowed verification of the simulation models. Both test results and simulations have been presented.

In general, it can be concluded that the TRANSFORMERS project resulted in three successful innovations being developed and demonstrated; namely centred around load optimization, aerodynamic measures, and Hybrid-on-Demand technologies. All have demonstrated high saving potentials when confronted with the project goals as shown in figure 8.1 below, each depending on the mission profile in their own way. Additionally, all innovations have shown the potential for a viable business case in the future and show even further improvement potential.

![Figure 8.1: project goals in terms of energy use reduction per tonnes*kilometres](image)

When reflecting the results of the testing and evaluation on the original goals of the project in terms of energy use reduction as summarized in the figure above, the following can be concluded:

- The Hybrid-on-Demand system shows highest potential with a relatively small battery (10 kWh) and large electric motor-generator (240 kW). The short term regeneration potential determines the energy use reduction potential, 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 saving potential of the boat tail is up to 3%, which equals the saving potential of the configurable roof. The combined savings add up to 6.5%. The goal of 8% is in reach, but it has to be noted that the impact of the optimized side wings and bulkhead are not included the results.

- The load optimization 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*kilometre. The double floor potential is dependent on the type of cargo. When assuming up to 5 tonne additional cargo, the energy use reduction compared to an original cargo payload of 8 tonne is up to 31%. In case of an original cargo payload of 15 tonnes, this is up to 17%.

When combining the three types of TRANSFORMERS innovations, the overall goal of 25% reduction of energy use can be reached. The variation of the combined results is obviously very wide, since the potential of each innovation is different for the type of routes or payload scenario. The characteristics of the innovations do not allow for limitless combinations. An example is that the double floor can be combined with a configurable roof in high or high tapered position only. Since aerodynamic measures show the highest
potential on motorway and the HoD on steep elevation changes, the combined potential with 5 tonne additional payload even exceeds 30% in these situations.

The economic assessment using realistic mixed scenario routes and their associated annual savings and related NPV, reveals that the TRANSFORMERS innovations show the potential for a viable business case. The highest potential for a positive business case is offered by the load optimization measures, followed by the aerodynamic measures and Hybrid-on-Demand.

The TRANSFORMERS innovations require further development before market introduction is possible. A quick scan on the savings potential shows the following important topics to work on in the near future, especially for the Hybrid-on-demand system:

• Weight reduction for the HoD system and aerodynamic measures may result in an additional 0.5 to 1% benefit in energy use reduction.
• 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. More investigation of the optimum system strategy for different routes is needed.
• The plug-in scenario does not show improvements for all cases simulated, but offers up to 4% higher fuel savings for some routes. More investigation of the optimum system strategy for plug-in systems is needed for different routes is needed.

The nature of the TRANSFORMERS approach is to consider the tractor-trailer combination as a complete vehicle, which can be reconfigured at 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 reconfigurable approach, the TRANSFORMER truck approach is able to combine the optimization potential, rather than the average fuel saving potential.

The VECTO tool for calculating the CO₂ emission from new conventional heavy-duty vehicles in the near future, does not allow yet for the TRANSFORMERS innovations. For the load optimisation and aerodynamic measures the VECTO can be adapted with limited effort. For the Hybrid-on-Demand innovation an extension is needed that considers strong impact of control/energy management strategies.

Within the context of the current and future market, recommendations are made towards the implementation of TRANSFORMERS results. The TRANSFORMERS innovations are potentially robust solutions and are on the road to the market, but are not there yet. It is challenging to innovate within the current rules and regulations, but not impossible. And finally, the approach to combine tractor and trailers, including the required cooperation between partners, is essential to reduce the energy used by transport in an optimal way.

Next Steps: So what needs to happen further?

- Continued cooperation is needed. An entire vehicle combination containing different independent concepts which could be used individually or together has been developed, involving different parties. The cooperation cannot stop here if we want to market the concepts.
- Cooperation will be required in:
  - Further optimising the concepts and their reliability
  - Application of concepts to other types of vehicles combinations
  - Testing in real life conditions with shippers and carriers
  - Testing interaction with other interesting concepts such as platooning, use of alternative fuels, high capacity vehicles.
  - Optimise communication tractor unit with semi-trailer (configurable roof, HoD, load capacity monitoring)
  - Fine-tune the business case - try to create markets of scale
  - Enable the concepts within the EU and national legal frameworks, especially relating to type approval (braking, masses and dimensions) and weights and dimensions (weight exemption for alternative fuel technology to apply to vehicle combinations)
  - Incentivise the concepts: legislative incentives and non-legislative incentives
- Finally, increased visibility and wide spread understanding of future project results should underpin widespread technical, market, and policy discussions.
9 References

The reference list is additional to the deliverable list of the TRANSFORMERS project, which will not be repeated here.

[3]  Adoption in TCMV, Brussels, 11 May 2017; HDV CO\textsubscript{2} Certification Regulation Final and Annexes 1 to 10, 6 April 2017
https://webgate.ec.europa.eu/CITnet/confluence/display/VECTO/VECTO+Home
[6]  Using a simplified Willans line approach as a means to evaluate the savings potential of CO2 reduction measures in heavy-duty transport, TAP conference 2016, Lyons
## Acknowledgment

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


http://ec.europa.eu

### PROJECT PARTICIPANTS:

<table>
<thead>
<tr>
<th>Project</th>
<th>Company/Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOLVO</td>
<td>VOLVO TECHNOLOGY AB(SE)</td>
</tr>
<tr>
<td>BOSCH</td>
<td>ROBERT BOSCH GMBH</td>
</tr>
<tr>
<td>DAF</td>
<td>DAF TRUCKS NV</td>
</tr>
<tr>
<td>FEHRL</td>
<td>FORUM DES LABORATOIRES NATIONAUX EUROPEENS DE RECHERCHE ROUTIERE</td>
</tr>
<tr>
<td>FHG</td>
<td>FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V</td>
</tr>
<tr>
<td>IFSTTAR</td>
<td>INSTITUT FRANCAIS DES SCIENCES ET TECHNOLOGIES DES TRANSPORTS, DE L'AMENAGEMENT ET DES RESEAUX</td>
</tr>
<tr>
<td>IRU</td>
<td>IRU PROJECTS ASBL</td>
</tr>
<tr>
<td>P&amp;G</td>
<td>PROCTOR &amp; GAMBLE SERVICES COMPANY NV</td>
</tr>
<tr>
<td>SCB</td>
<td>SCHMITZ CARGOBULL AG</td>
</tr>
<tr>
<td>TNO</td>
<td>NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK (NL)</td>
</tr>
<tr>
<td>UNR</td>
<td>UNIRESEARCH BV (NL)</td>
</tr>
<tr>
<td>VEG</td>
<td>VAN ECK BEESD BV</td>
</tr>
<tr>
<td>VIF</td>
<td>KOMPETENZZENTRUM - DAS VIRTUELLE FAHRZEUG, FORSCHUNGSGESELLSCHAFT MBH</td>
</tr>
</tbody>
</table>

### DISCLAIMER

The FP7 project has been made possible by a financial contribution by the European Commission under Framework Programme 7. The Publication as provided reflects only the authors’ view.

Every effort has been made to ensure complete and accurate information concerning this document. However, the author(s) and members of the consortium cannot be held legally responsible for any mistake in printing or faulty instructions. The authors and consortium members retrieve the right not to be responsible for the topicality, correctness, completeness or quality of the information provided. Liability claims regarding damage caused by the use of any information provided, including any kind of information that is incomplete or incorrect, will therefore be rejected. The information contained on this website is based on author’s experience and on information received from the project partners.
## Appendix List

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Evaluation approach</td>
</tr>
<tr>
<td>A.1</td>
<td>Roadload model</td>
</tr>
<tr>
<td>A.2</td>
<td>Powertrain models using Willans-line approach</td>
</tr>
<tr>
<td>A.3</td>
<td>Hybrid Willans line powertrain models for HoD axle</td>
</tr>
<tr>
<td>A.4</td>
<td>Parametrized hybrid Willans-line models</td>
</tr>
<tr>
<td>A.5</td>
<td>SoC correction for fuel consumption in high fidelity simulations</td>
</tr>
<tr>
<td>A.6</td>
<td>Validation of the hybrid Willans-line model</td>
</tr>
<tr>
<td>B</td>
<td>Detailed evaluation results</td>
</tr>
</tbody>
</table>
Appendix A – Evaluation approach

This chapter provides a detailed overview of the approach used to determine the savings potential of all TRANSFORMERS innovations. The model structure is shown in Figure A.1 and described in the following sections.

Figure A.1 Model structure to obtain fuel consumption for all use cases

A.1 Roadload model

The roadload model used in the impact assessment model to go from velocity and slope to roadload power demand is described here. The expression for the roadload power demand, in Watts, for a vehicle driving a certain route is:

\[ P_{road} = F_{road} \cdot v \]

where \( F_{road} [N] \) is the total road load force and \( v [m/s] \) is the actual vehicle speed,

\[ F_{road} = m g \sin \alpha + \frac{1}{2} \rho_{air} C_d A v^2 + m g c_r \cos \alpha + m_{eq} a \]

\[ F_{road} = F_{road} \cdot v \]

where \( \alpha [rad] \) is the road slope, \( g [m/s^2] \) is the gravitational constant, \( \rho_{air} [kg/m^3] \) is the air density, \( C_d \) is the coefficient of aerodynamic drag, \( A [m^2] \) is the vehicle frontal area, \( c_r [-] \) is the coefficient of rolling resistance, \( a [m/s^2] \) is the acceleration and \( m [kg] \) is total vehicle mass:

\[ m = m_{payload} + m_{tractor} + m_{trailer} \]

And \( m_{eq} \) represents the equivalent mass for acceleration, and includes the contribution of rotating elements such as wheels, driveshafts and engine.

A.2 Powertrain models using Willans-line approach

The fuel consumption of a vehicle is determined using a Willans-line approach [6]. This approach provides an affine mapping between roadload power and fuel rate and is typically used to describe fuel consumption of powertrains using internal combustion engines. The affine mapping consists of:

- a constant fuel consumption, independent of power, accounting for idling losses and/or auxiliary loads, and
- a fuel consumption term linear with roadload power, that accounts for the engine/powertrain efficiency in producing mechanical work.
This affine function holds for positive roadloads. For zero or negative roadloads, such as braking events, the constant fuelrate is adopted, accounting for engine idling and auxiliary loads. The Willans-line model has the following form:

\[
\dot{\text{rt}_f} = \begin{cases} 
  p_1 P_{\text{road}} + p_2 f & \text{for } P_{\text{road}} \geq 0 \\
  p_2 f & \text{for } P_{\text{road}} < 0
\end{cases}
\]

Model parameters can be derived from measurement data of fuelrate and engine- or powertrain-power through a linear fit, as illustrated in Figure A.2. The corresponding powertrain efficiency, from the fuel’s lower heating value to the energy at the tractor wheels, is also plotted. The shape of the efficiency curve is increasing for higher power. If a quadratic instead of linear Willans-line is adopted, an efficiency maximum would be introduced, where efficiency drops of again for maximum powers. The parameters obtained by fitting the Willans-line to all the fuelrate and wheel power datapoints from the high fidelity simulations are shown in Table A.1.

![Figure A.2 Example of a Willans-line model fit to a dataset of fuel rate and power, for a conventional non-hybrid vehicle, and the corresponding powertrain efficiency](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description [dimension]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_1)</td>
<td>(2.00 \times 10^{-4} \text{ [l/Wh]})</td>
</tr>
<tr>
<td>(p_2)</td>
<td>(5.43 \text{ [l/h]})</td>
</tr>
</tbody>
</table>

The accuracy achieved using this model approach to predict the fuel consumption of the non-hybrid vehicle-configurations is presented in Figure A.3, and are within 6% of total absolute fuel consumption, compared to the high fidelity simulations. The average error is 0.7% and the standard deviation is 2.6%. However, the value of the Willans-line approach to assess potential fuel savings lies not in the absolute prediction of fuel consumption values, but in the ability to assess many different use cases with different vehicle configurations and technologies with minimal effort, and thus allow comparison between vehicle technologies. It is the difference in fuel consumption between different vehicle configurations that is of largest interest to assess the benefit of the proposed technologies. In the TRANSFORMERS context, this concerns predominantly the fuel savings due to the Hybrid on Demand system, treated in the next section.
Figure A.3 Fuel consumption comparison between TNOs Willans-line model and ViF high fidelity simulations for non-hybrid, conventional vehicles.

A.3 Hybrid Willans line powertrain model for HoD axle

The fuelrate function for the extended Hybrid Willans-line is given by:

$$\dot{m}_f = \begin{cases} p_1 P_{road} + p_2 & \text{for } P_{road} \geq 0 \\ n_1 P_{regen} + n_2 & \text{for } P_{road} < 0 \end{cases}$$

With

$$n_1 = \eta_{hybrid} P_1$$

And

$$P_{Regen} = \max(P_{road}, -\max EMG power, -\max EMG torque \cdot EMG speed)$$

In this work, the $p_2$ and $n_2$ coefficients, corresponding to engine idling and auxiliary losses independent of roadload, are chosen equal. Note that the value of coefficient $n_1$ is always smaller than that of $p_1$; a negative roadload can never result in more fuel saved than the fuel used for a positive roadload of equal magnitude. The ratio between $p_1$ and $n_1$ is given by the hybrid efficiency $\eta_{hybrid}$. The $\eta_{hybrid}$ coefficient sets the proportionality between regeneration power and motor-assist power. The value of this coefficient represents the total efficiency of all energy conversion steps from negative mechanical roadload, to motor-generator power, to recuperated battery energy, back to motor generator power and positive roadload. The product of $\eta_{hybrid}$ and $n_1$ and then gives the proportionality between regenerated energy and fuel saved. The shape of the hybrid Willans line model is presented graphically in Figure A.4.
A.4 Parametrized hybrid Willans-line models

The value of $\eta_{\text{hybrid}}$ is can be derived from high fidelity simulations, and varies between 60% for low speed cycles to 80% for high speed cycles. The difference in efficiency is the result of the efficiency map of the EMG, which peaks at higher speeds and torque, which are more common at higher vehicle velocities. It was therefore chosen to adopt different hybrid efficiencies $\eta_{\text{hybrid}}$ for urban and motorway cycles. For urban cycles, a hybrid efficiency of 60% is adopted, while for motorway cycles a hybrid efficiency of 77% is used. The effect of different torque and power ratings of the electric motor generator are accounted for in the equation for the regeneration power $P_{\text{regen}}$. The different combinations of power and torque ratings are presented in Table A.2. From the set of high fidelity simulations, no relation between hybrid efficiency and battery capacity was observed, and so this parameter is not used in the models of the evaluation framework.

<table>
<thead>
<tr>
<th>Motor-generator power</th>
<th>Motor-generator torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kW</td>
<td>100 Nm</td>
</tr>
<tr>
<td>80 kW</td>
<td>200 Nm</td>
</tr>
<tr>
<td>160 kW</td>
<td>400 Nm</td>
</tr>
<tr>
<td>240 kW</td>
<td>600 Nm</td>
</tr>
</tbody>
</table>

A.5 SoC correction for fuel consumption in high fidelity simulations

During this cycle, there is a net-difference between the battery state of charge at the start and the end of the cycle in the high fidelity simulation results. A direct comparison between the high-fidelity fuel consumption result and the Willans-line fuel consumption is therefore not possible; the difference in SoC in the high-fidelity simulation must first be corrected. The Willans-line model implicitly represents a charge-sustaining situation; all energy recuperated during negative roadloads is immediately accounted for as a fuel saving, using the corresponding efficiency. However, SoC limitations are indirectly implemented, because the model uses the average hybrid efficiency of VIF’s simulations. SoC limitations are reflected in the hybrid efficiency, since under certain conditions no regeneration and/or no boosting is possible. During the evaluation, the fitted model for hybrid powertrains is used in combination with other TRANSFORMERS innovations on the same routes.

A.6 Validation of the hybrid Willans-line model

The validity of the hybrid Willans-line model, is confirmed by comparing predicted fuel savings that would result from the implementation of the Hybrid on Demand (HoD) system. The basis for this comparison is the calculated fuel consumption for different scenarios (with the same route and payload) for the different HoD configurations as well as for the corresponding non-hybrid configuration. This comparison is shown in the bottom half of Figure A.3 for 5 different scenarios and two different HoD specifications (80kW/20kWh and 240kW/20kWh).
Figure A.3 Validation of Hybrid-Willans Line model by comparison to high-fidelity simulation results

Table A.3 gives an overview of the different combinations and of the corresponding simulation index presented in this figure. The trend of relative fuel savings is reproduced well by the hybrid Willans-line model, with most errors within 1% in terms of fuel saving due to the HoD system when compared to high-fidelity simulations.

Table A.3 Scenarios and HoD configurations corresponding to simulation index in Figure A.3

<table>
<thead>
<tr>
<th>Simulation Index</th>
<th>Scenario / traffic</th>
<th>HoD config</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1 / Low</td>
<td>80kW/20kWh</td>
</tr>
<tr>
<td>2</td>
<td>S2 / Med</td>
<td>80kW/20kWh</td>
</tr>
<tr>
<td>3</td>
<td>S3 / Med</td>
<td>80kW/20kWh</td>
</tr>
<tr>
<td>4</td>
<td>S4 / Med</td>
<td>80kW/20kWh</td>
</tr>
<tr>
<td>5</td>
<td>S5 / Med</td>
<td>80kW/20kWh</td>
</tr>
<tr>
<td>6</td>
<td>S1 / Low</td>
<td>240kW/20kWh</td>
</tr>
<tr>
<td>7</td>
<td>S2 / Med</td>
<td>240kW/20kWh</td>
</tr>
<tr>
<td>8</td>
<td>S3 / Med</td>
<td>240kW/20kWh</td>
</tr>
<tr>
<td>9</td>
<td>S4 / Med</td>
<td>240kW/20kWh</td>
</tr>
<tr>
<td>10</td>
<td>S5 / Med</td>
<td>240kW/20kWh</td>
</tr>
</tbody>
</table>
Appendix B – Detailed evaluation results

The tables below show the evaluation results of the three TRANSFORMERS technologies A, B and C for a maximum of three different levels: low potential, middle potential and high potential:

- **Loading efficiency increase due to flexible floor (A)**
  - Low potential results: 1 tonne additional payload
  - Middle potential results: 3 tonnes additional payload
  - High potential results: 5 tonnes 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

The current savings potential of the TRANSFORMERS innovations is shown in Table B.1 with assumptions on the additional payload of technologies as described in section 5.3. The future potential is shown in Table B.2 for TRANSFORMERS innovations with no additional weight constraints. The results are discussed in the main body of this report.
<table>
<thead>
<tr>
<th>road type</th>
<th>topology</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>urban</td>
<td>flat</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>motorway</td>
<td>flat</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>road type</th>
<th>topology</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
<th>8 tons</th>
<th>15 tons</th>
<th>25 tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>urban</td>
<td>flat</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>motorway</td>
<td>flat</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>road type</td>
<td>urban</td>
<td>motorway</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>----------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>congestion</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>payload</td>
<td>8 tons</td>
<td>15 tons</td>
<td>25 tons</td>
<td>8 tons</td>
<td>15 tons</td>
<td>25 tons</td>
<td>8 tons</td>
<td>15 tons</td>
<td>25 tons</td>
<td>8 tons</td>
<td>15 tons</td>
<td>25 tons</td>
<td>8 tons</td>
<td>15 tons</td>
<td>25 tons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[HF+NBT / noHOD]</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A low</td>
<td>-5%</td>
<td>-1%</td>
<td>0%</td>
<td>-6%</td>
<td>-1%</td>
<td>0%</td>
<td>-6%</td>
<td>-2%</td>
<td>0%</td>
<td>-8%</td>
<td>-3%</td>
<td>-1%</td>
<td>-8%</td>
<td>-3%</td>
<td>-1%</td>
<td>-8%</td>
<td>-3%</td>
<td>-1%</td>
<td>-6%</td>
<td>-2%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A med</td>
<td>-18%</td>
<td>-8%</td>
<td>-3%</td>
<td>-19%</td>
<td>-9%</td>
<td>-4%</td>
<td>-19%</td>
<td>-9%</td>
<td>-6%</td>
<td>-22%</td>
<td>-11%</td>
<td>-5%</td>
<td>-22%</td>
<td>-11%</td>
<td>-5%</td>
<td>-19%</td>
<td>-9%</td>
<td>-4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A high</td>
<td>-27%</td>
<td>-13%</td>
<td>-6%</td>
<td>-28%</td>
<td>-14%</td>
<td>-7%</td>
<td>-28%</td>
<td>-13%</td>
<td>-7%</td>
<td>-32%</td>
<td>-18%</td>
<td>-9%</td>
<td>-31%</td>
<td>-17%</td>
<td>-9%</td>
<td>-27%</td>
<td>-13%</td>
<td>-9%</td>
<td>-14%</td>
<td>-7%</td>
<td>-4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B low</td>
<td>-2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B med</td>
<td>-8%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B high</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C low</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C med</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C high</td>
<td>-20%</td>
<td>-17%</td>
<td>-15%</td>
<td>-19%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+B</td>
<td>-5%</td>
<td>-1%</td>
<td>0%</td>
<td>-6%</td>
<td>-2%</td>
<td>0%</td>
<td>-6%</td>
<td>-2%</td>
<td>0%</td>
<td>-13%</td>
<td>-8%</td>
<td>-10%</td>
<td>-17%</td>
<td>-8%</td>
<td>-10%</td>
<td>-17%</td>
<td>-8%</td>
<td>-10%</td>
<td>-17%</td>
<td>-8%</td>
<td>-10%</td>
<td>-17%</td>
<td>-8%</td>
<td>-10%</td>
<td>-17%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+B+C</td>
<td>-18%</td>
<td>-8%</td>
<td>-3%</td>
<td>-19%</td>
<td>-9%</td>
<td>-4%</td>
<td>-19%</td>
<td>-9%</td>
<td>-6%</td>
<td>-24%</td>
<td>-13%</td>
<td>-7%</td>
<td>-24%</td>
<td>-13%</td>
<td>-7%</td>
<td>-21%</td>
<td>-10%</td>
<td>-5%</td>
<td>-24%</td>
<td>-13%</td>
<td>-7%</td>
<td>-21%</td>
<td>-10%</td>
<td>-5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+C</td>
<td>-27%</td>
<td>-14%</td>
<td>-7%</td>
<td>-28%</td>
<td>-15%</td>
<td>-7%</td>
<td>-29%</td>
<td>-13%</td>
<td>-8%</td>
<td>-33%</td>
<td>-22%</td>
<td>-13%</td>
<td>-34%</td>
<td>-21%</td>
<td>-12%</td>
<td>-35%</td>
<td>-21%</td>
<td>-12%</td>
<td>-35%</td>
<td>-21%</td>
<td>-12%</td>
<td>-35%</td>
<td>-21%</td>
<td>-12%</td>
<td>-35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+C+D</td>
<td>-3%</td>
<td>-4%</td>
<td>-1%</td>
<td>-12%</td>
<td>-7%</td>
<td>-5%</td>
<td>-13%</td>
<td>-8%</td>
<td>-6%</td>
<td>-25%</td>
<td>-13%</td>
<td>-9%</td>
<td>-30%</td>
<td>-10%</td>
<td>-5%</td>
<td>-30%</td>
<td>-10%</td>
<td>-5%</td>
<td>-30%</td>
<td>-10%</td>
<td>-5%</td>
<td>-30%</td>
<td>-10%</td>
<td>-5%</td>
<td>-30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B+C</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-7%</td>
<td>-6%</td>
<td>-5%</td>
<td>-11%</td>
<td>-8%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B+C+D</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td>-10%</td>
<td>-14%</td>
<td>-12%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+D</td>
<td>-20%</td>
<td>-18%</td>
<td>-15%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td>-18%</td>
<td>-16%</td>
<td>-20%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A+B+C+D</td>
<td>-12%</td>
<td>-7%</td>
<td>-4%</td>
<td>-12%</td>
<td>-7%</td>
<td>-5%</td>
<td>-13%</td>
<td>-8%</td>
<td>-6%</td>
<td>-17%</td>
<td>-7%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
<td>-4%</td>
</tr>
<tr>
<td>A+B+C+D+H</td>
<td>-29%</td>
<td>-18%</td>
<td>-13%</td>
<td>-30%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td>-28%</td>
<td>-20%</td>
<td>-14%</td>
<td></td>
</tr>
</tbody>
</table>

Table B.2 Future potential of TRAMERs technologies in terms of effectiveness %/ton.km.MP

For more detailed information, please refer to the Final Report and Conclusions.