AEROFLEX

Aerodynamic and Flexible Trucks for Next Generation of Long Distance Road Transport

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Publishable Executive Summary

As overall objective, AEROFLEX WP2 aims to reduce fuel consumption of EMS vehicles by advanced powertrain technology. A key idea is to combine the combustion engine of the pulling vehicle with electric drives in different vehicle units, thereby creating a distributed hybrid drive. In turn AEROFLEX vehicles would allow a flexible combination of vehicle units which bring their own driveline into the combination. A sophisticated energy and torque management system will allow an efficient operation of this distributed powertrain. This type of powertrain architecture including at least one electric drive in a trailer unit, the sophisticated energy and torque management and a suitable communication interface is referred to as Advanced Energy Management Powertrain (AEMPT).

This report presents requirements to an AEMPT from different aspects: Relevant vehicle portfolio, energy and power demand for reaching efficiency goals, energy management and vehicle dynamics. These requirements will form the basis for concrete technical solutions which will be presented in D.2.2

The portfolio of vehicles which have to be considered as AEMPT relevant has been chosen in line with the findings of the FALCON project. Accordingly, AEMPT vehicles may include up to four trailer units, have a length of up to 36,5 m and a gross combination weight of 91,6 tons.

In order to derive requirements to battery capacity and electric power of AEMPT vehicles, simulations have been conducted using a low detail simulation model. This model allowed to calculate initial fuel saving potentials for different vehicle configurations assuming a simple energy management. The results show that AEMPT vehicles should have a battery capacity of 0,35kWh/ton GCW and an electric power rating of 4kW/ton GCW. These values allow fuel savings of up to 8,5% on typical long haul cycles. A sophisticated energy management may further increase this number.

For the energy management architecture, basic requirements are presented. Based on these findings a functional structure will be set up in the course of the project. In favour of maximum energy efficiency, a decision has been taken toward a centralized structure. A global energy and torque management system will communicate with multiple local system management instances in the trailer units. A suitable communication protocol will ensure the required flexibility in combining vehicle units.

Including a powerful distributed hybrid drive into long haul trucks, in particular EMS vehicles, of course may substantially influence vehicle dynamics. Looking at driveability, a distributed powertrain shows advantages in traction, as more weight is carried by driven axles. Requirements have been derived for electric torque and for power ratings of the electric drives and the combustion engine. For lateral dynamics, electrically driven axles may lead to unwanted behaviour in articulated vehicles. Following the general idea that AEMPT vehicles shall fulfil the same stability criteria as conventional vehicles, reference is made to the Australian Performance Based Standards for high capacity vehicles. However, multibody simulations show that additional criteria are necessary to account for the influence of electric drives.

The performance of AEMPT vehicles will be rated by in total 15 KPIs defined in this document. These KPIs cover efficiency, lateral stability, driveability and manoeuvrability. By adding target values to KPIs, they are also part of a list of 54 requirements to AEMPT vehicles. For vehicle configurations which cannot be rated in real world tests, the KPIs will be calculated in suitable simulations.

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List of Abbreviations

AEMPT *Advanced Energy Management Powertrain, Advanced Energy Management Powertrain*
EMG *Electric Motor Generator*
EMS *European Modular System*
GCW Gross Combination Weight, Gross Combination Weight
GETMS *Global Energy and Torque Management System*
HOD *Hybrid on Demand*
HV *High Voltage, High Voltage*
LHV Long and Heavy Vehicle
LSM *Local System Management*

Purpose of the document

In AEROFLEX WP2 a powertrain architecture for EMS-vehicles which include electric drives in multiple vehicle units will be developed. A sophisticated energy and torque management system will allow an efficient operation of this distributed powertrain. This powertrain architecture is referred to as Advanced Energy Management Powertrain (AEMPT).

This document aims to outline general requirements to AEMPT vehicles which shall be valid to any vehicle configuration out of a specified EMS vehicle portfolio. Based on these requirements, concrete technical solutions like a function structure or a communication protocol will be developed. Moreover, demo vehicles of WP2 are being developed in accordance to the findings of this document. The description of the technical solutions will be part of D2.2.

1 Introduction

The overall objective of AEROFLEX WP2 is to reduce fuel consumption of EMS vehicles by advanced powertrain technology. A key idea is to combine a conventional or hybrid powertrain of the pulling vehicle with electric drives in other vehicle units, thereby creating a distributed hybrid drive. This concept might allow to install a downsized combustion engine which is supported by electric drives in the trailer units, if coupled to the truck. In turn AERO**FLEX** vehicles would allow a **flexible** combination of vehicle units which bring their own driveline into the combination.

Figure 1 Flexible combination of driven vehicle units (1)

In the Transformers Project (2) a first step was taken to explore the potential of a distributed driveline by combining a conventional tractor unit with an electrified trailer. Such a concept is also referred to as Hybrid on Demand (HOD), as the hybrid driveline is only formed when coupling tractor and semitrailer. In Transformers, the communication between tractor and e-Trailer was limited to a minimum in order to make the system retro-fit capable. The control of the electric drive was only based on brake and acceleration requests of the driver or the cruise control system. There has been no integration into the control systems of the tractor unit. In other words, the tractor unit did not know what the trailer was doing. Such an approach is advantageous in terms of simple integration. However it comes to limits if the electric power is raised to an level which substantially effects the overall vehicle behaviour.

AEROFLEX WP2 aims to reduce fuel consumption up to 12% by hybrid powertrain technology. To reach this goal, a very efficient system is necessary. Accordingly, starting from the Transformers solution, AEROFLEX WP2 will take the next step and deeply integrate separate drive units in an efficient powertrain system. In the following, this system is referred to as Advanced Energy Management Powertrain (AEMPT). Such a concept raises many questions:

- What should be the energy capacity and power of electrified units? To little power or energy will not allow reaching the targeted fuel reduction. Too high power or energy will result in too much costs and weight.
- How can a distributed powertrain be managed efficiently?
- How do the vehicle units communicate? This question refers to both the communication technology as well as the data which is sent and received by the vehicle units.
- How do electric motors in trailer units influence vehicle dynamics? High available power in electric axles of trailer units can influence vehicle dynamics in a non-favourable way. High attention will be put on this issue as it is very relevant to a safe operation of the vehicle.
- What is the influence to traction capability? For EMS vehicles, weight is distributed among more axles. A distributed powertrain can help providing enough traction in high slope and/or low mu conditions.

This document shall give answers to these questions and accordingly put requirements on the development process of the AEMPT Architecture. What this document will not give are technical solutions which fulfil these requirements.

Section 2 will explain the vehicle portfolio of a future European EMS landscape. Reference to the FALCON project is made which gives an excellent starting point in terms of relevant vehicles.

Section 3 describes the assessment which was done to derive requirements for energy and power demand. By using a low fidelity simulation tool, numbers could be derived without already knowing any sophisticated energy management strategy.

Section 4 gives basic requirements for an energy management system.

Section 5 gives requirements to vehicle dynamics of an AEMPT vehicle. Again, reference is made to FALCON which presented a Performance Based Standards SCHEME for EMS vehicles in Europe

Section 7 gives detailed definitions to KPIs which will be used to assess the performance of AEMPT vehicles throughout the project.

Appendix A contains all simulation results of the low fidelity energy demand simulations presented in section 4.

Appendix B lists all requirements derived in the sections 3 to 6 in a single table.

2 Vehicle Portfolio

2.1 Reference to FALCON

In the FALCON Project (2), a representative fleet for future EMS vehicles in Europe has been defined. Focus was put on standardized transport units like swap bodies or containers in order to account for multimodality. The fleet includes vehicles which are already allowed in some member states of the EU and vehicles which are tested in pilot programs. In the following, vehicles up to 25.25 m will be referred to as EMS1 vehicles. Longer vehicles will be referred to as EMS 2 vehicles. Table 1 shows FALCON representative fleet:

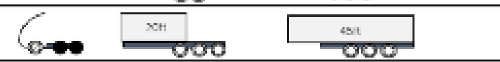
Vehicle group and code +		Vehicle description	Length (m)	Mass (r/c) (tonnes)	
1.1	TR6x2-ST3 (45ft)		16.2	33.5	41.3
1.2	TR6x2-ST3 (2x7.8m)		18.5	37.4	46.2
1.3	TR4x2-ST3 (13.6m)		16.4	29.7	37.7
1.4	TR4x2-ST3 (14.9m)		17.7	31.8	43.3
2.1	TK6x2-CT2 (2x7.8m)		19.3	35.4	44.3
2.2	TK6x2-FT1+1 (2x7.8m)		18.5	35.4	44.3
2.3	TK6x2-CT3(2x20ft)		16.9	29.8	35.9
3.1	TR6x4-ST3-CT3(45ft+20ft)		23.7	47.3	58.1
3.2	TR6x4-ST3-CT2(3x7.8m)		27.9	53.3	66.6
3.3	TR6x4-LT2-ST3(3x7.8m)		27.7	56.1	69.4
3.4	TR6x4-LT3-ST3(20ft+45ft)		23.9	48.5	59.3
4.1	TK6x4-DY2-ST3 (3x7.8m)		26.7	53.2	66.5
4.2	TK6x4-FT2+3 (3x7.8m)		26.7	53.2	66.5
4.3	TK6x4-DY2-ST3 (20ft+45ft)		24.4	46.0	56.8
4.4	TK6x4-FT2+3 (20ft+45ft)		25.0	47.0	57.8
4.5	TK6x4-CT2-CT2 (3x7.8m)		27.9	51.4	64.7
4.6	TK8x4-CT3-CT3(3x20ft)		24.3	43.2	52.4
4.7	TK8x4-FT2+3(20ft+45ft)		24.9	46.7	57.6
5.1	TR6x4-ST3-DY2-ST3 (2x45ft)		31.1	62.6	78.2
5.2	TR6x4-ST3-FT2+3 (2x45ft)		31.6	63.6	79.2
5.3	TR6x4-LT2-LT2-ST3 (4x7.8m)		36.5	73.8	91.6
5.4	TR6x4-LT3-LT3-ST3 (2x20ft+45ft)		31.2	62.5	76.4
6.1	TK6x4-DY2-LT2-ST3 (4x7.8m)		35.4	71.0	88.7
6.2	TK6x4-DY2-LT2-ST3 (2x7.8m+45ft)		31.7	60.0	73.9
6.3	TK6x4-CT2-CT2-CT2 (4x7.8m)		36.5	66.5	84.2

Table 1 FALCON representative fleet

2.2 Findings of WP1

Based on the findings of FALCON, Work Package 1 of AEROFLEX investigated the potential of the proposed EMS configurations. In expert interviews it has been tried to identify configurations which are most likely to play a major role in the future European transport market (3). However, this approach did not result in a clear picture which allows valid recommendations of a small number of suitable configurations. For now, it has to be concluded that due to the complexity of the logistics market, for each EMS configuration out of the FALCON representative fleet there might be a specific use-case which make this configuration the most favourable.

2.3 Focus of WP2

When looking on the large number of EMS-configurations identified in FALCON, it becomes obvious that the scope of AEROFLEX WP2 does not allow to assess each of them in terms of fuel saving potential or vehicle dynamics. Moreover, besides deriving general AEMPT-requirements which hold true for all possible EMS configurations this work shall of course be a base for the demonstrator vehicles which finally will physically be handed over to WP6 for measurements. Therefore, wherever an assessment of specific configurations becomes necessary, the focus will be on the following vehicles:

- 4x2 Tractor – Semitrailer: This is the most common configuration for long haul transport in Europe and therefore the base line for all assessment done in WP2. The Transformers project already showed the potential of such a configuration including an e-Trailer (2).
- 6x2 Truck –Dolly – Semitrailer (EMS1): This vehicle complies with the 25.25m length restriction for LHVs currently valid for Sweden, The Netherlands, Belgium, Denmark and Germany.
- 4x2 Tractor- Semitrailer-Dolly-Semitrailer (EMS2): This configuration, also known as A-double is already in operation in Finland and Spain.

2.4 Requirements to the AEMPT

Looking at the FALCON vehicle portfolio and on findings of WP1, it becomes clear that the AEMPT Architecture cannot be restricted to a few specific configurations but should be suited to all configurations which can be created by coupling together multiple vehicle units up to a maximum of 36,5m. The representative fleet of Table 1 highlights that vehicle units to be considered may be tractor units, trucks, trailers, dollies and semitrailers. A vehicle combination can be made up by up to four vehicle units and accordingly a maximum of three articulations. The following table summarizes AEMPT requirements imposed by the vehicle portfolio:

Table 2 Vehicle Portfolio Requirements to the AEMPT

Index	Dependent from Index	Category	Requirements	Comment/KPIs
VP - 1		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to four vehicle units (up to 3 trailer units)	
VP - 2		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to 36,5m	
VP - 3		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to a GCW of 91,6 tons	
VP – 4		Vehicle Portfolio	As trailer units, an AEMPT vehicle shall be able to include full trailers, semi-trailers and dollies	

3 Energy Demand

3.1 Motivation

TNO conducted initial simulations to estimate the potential of fuel consumption reduction for various vehicle configurations, electric power densities, payloads and mission profiles. This was achieved through TNO's MEO model. The results are available in (4). From these simulations, a too optimistic result is expected for heavy vehicles during down-hill driving due to a lack of constraints in battery capacity.
Based on the results of the initial simulations, MAN highlighted being interested in the use of these results to assist in the selection of the battery capacity for the development of the AEMPT demonstrator. Nevertheless, the lack of a realistic battery capacity behaviour limits the usability of the assessment for that purpose. Extending the MEO model with a more realistic battery capacity functionality and a simple hybrid control strategy which is required inevitably is of interest to both TNO and MAN. New simulations are then performed with the aforementioned extended functionality. This new development will also be of use for the WP6 final assessment of the AEROFLEX innovations.

3.2 Objectives

The report "AEROFLEX-WP2 Initial MEO Simulations Results-2018.03.23.pdf (4)" presents an overview of the fuel saving potential of the AEMPT powertrain over a wide range of scenarios with the purpose of assisting the activities of WP2 towards the driveline architecture. Nevertheless, it was then realised that further work was required to obtain an analysis that would also support the selection of battery sizing.

The objective of the present work is threefold:

- Supporting WP2 in selecting the hybrid component sizing (battery and electric motor) for a distributed powertrain containing of tractor semi-trailer, EMS1 and EMS2 vehicle configurations;
- Provide overview of the overall potential of distributed powertrains for certain vehicle types in different applications independent of the AEMPT demonstrator vehicle;
- Extending the MEO simulation tool for usage in the final assessment of WP6.

Table 3 provides a list of terms used throughout this report.

Table 3 List of definitions

Concept	Definition
Vehicle configuration	Examples: • Tractor-semitrailer (16.5 [m]) • Truck-dolly-trailer (25.25 [m]) • Tractor-semitrailer-dolly-semitrailer (32 [m])
Vehicle specification	Main vehicle parameters: total weight, rolling resistance, effective frontal area (Cd*A), payload-capacity, EMG-power & torque
Use Case	Realistic/real daily operation of a logistics operator
Test case	Scenario to be tested on physical vehicle
Scenario	Mission profile with a certain vehicle
Mission profile	Speed/slope/payload as function of time or distance for a certain type of road, degree of congestion and elevation pattern.
Trip	A vehicle traveling a defined trajectory from origin to destination (consists of one or more different mission profiles)

All treated scenarios will be assessed in terms of two Key Performance Indicators (KPI's):

- KPI 1: fuel efficiency in [litre/(tonne-km)] and its corresponding percentage fuel consumption reduction compared to the reference vehicle (the impact on fuel consumption is equivalent to the impact on the emissions of gram CO_2 per tonne-cargo per kilometre)
    - Equation absolute numbers:
        - $\frac{Fuel\ consumption\ [litre\ ]}{payload\ [tonne] \cdot distance\ [km]}$
    - Equation relative numbers:
        - $\frac{\left(Fuel\ consumption\ reference\ vehicle\ \left[\frac{l}{tonne \cdot km}\right] - Fuel\ consumption\ vehicle\ with\ feature\ \left[\frac{l}{tonne \cdot km}\right]\right)}{Fuel\ consumption\ reference\ vehicle\ \left[\frac{l}{tonne \cdot km}\right]} \cdot 100\%$

- KPI 2: fuel consumption in [l/km] and its corresponding percentage fuel consumption reduction compared to the reference vehicle (to compare different vehicle configurations carrying the same payload)
    - Equation absolute numbers:
        - $\frac{Fuel\ consumption\ [litre\ ]}{distance\ [km]}$
    - Equation relative numbers:
        - $\frac{\left(Fuel\ consumption\ reference\ vehicle\ \left[\frac{l}{km}\right] - Fuel\ consumption\ vehicle\ with\ feature\ \left[\frac{l}{km}\right]\right)}{Fuel\ consumption\ reference\ vehicle\ \left[\frac{l}{km}\right]} \cdot 100\%$

3.3 Vehicle configurations

This analysis will treat three vehicle configurations:

1. Tractor-semitrailer
2. EMS1: Tractor-dolly-semitrailer
3. EMS2: Tractor-semitrailer-dolly-semitrailer

and schematically depicted as:

Configuration 1

Configuration 2

Configuration 3

Figure 2 Vehicle combinations considered in this study

Table 4 shows the main parameters of these vehicle configurations. These parameters were chosen by reviewing information of comparable vehicles. These parameters are merely indicative since the AEROFLEX project is in an early stage, but are typical values for these type of vehicle configurations. These parameters are then suitable for the purpose of showing the potential of the different powertrain innovations. The values applied here are identical compared to the values used in (5).

Table 4 Main parameters of the presented vehicle configurations

Vehicle configuration	Rolling resistance ($\mu_{rolling}$) [-]	Effective frontal area (Cd*A) [m^2]	Weight empty vehicle (m_{empty}) [tonne]	Gross Vehicle Weigth (GVW) [tonne]	Load capacity [tonne]
1. Tractor-Semitrailer	0.006	7	14	40	26
2. EMS1	0.006	8	19	60	41
3. EMS2	0.006	9	24	74	50

3.4 Powertrain configurations

Different powertrain configurations are analysed. The configurations where no hybridisation is present will be called 'conventional diesel'. All the other powertrain configurations are identified by the (Electric Motor-Generator) EMG power and the battery capacity. It is important to remark that all EMG components in each configuration are lumped as a single EMG. E.g. a configuration having 2 EMG machines with a rated power of 20 [kW] each will be considered as a single EMG with a rated power of 40 [kW]. Batteries are also considered as a single lumped component. E.g. a configuration having 2 batteries with capacity of 20 [kWh] each will be considered as a single battery with a capacity of 40 [kWh].
The electric drive units and their corresponding batteries add weight to the vehicles. This can either increase the total vehicle weight, or in the case of a fully loaded vehicle, reduce the payload capacity. GVW limits are enforced in all simulations, meaning that for fully loaded vehicles, the payload is reduced when a bigger AEMPT powertrain is used. In some countries, a higher GVW and/or axle load is allowed for certain vehicle types when electrified axles are used. However, such changes in allowed GVW with hybridization or electrification are not considered in this study, meaning that the allowed GVW is kept constant according to the values depicted in Table 4.

3.5 Mission profiles

For this simulation study, drive cycles from the EU Transformers project are adopted. These drive-cycles are described in Table 5.

Table 5 Drive-cycles extracted from Transformers project (italic marked routes are out of scope)

#	Route	Distance [km]	Avg speed Std dev speed [km/h]
S1	Flat highway	157	75.4 16
S2	*Highway mixed environments*	*363*	*86.4* *10*
S3	Frequent elevation changes	120	87.1 6
S4	Mountain pass	51,2	75.9 15
S5	*Urban*	*4,5*	*22.8* *13*

From these cycles, the Urban cycle (S5) is considered not relevant for the long-heavy vehicles treated in the AEROFLEX project, and cycles S2 and S3 are considered to be very similar. Because of this, the longer cycle S2 is not considered, to save on computation and analysis time. Therefore, the fuel consumption results presented in this report concern cycles S1, S3 and S4.
In this extended initial study, the same speed-profiles are applied to all vehicle classes. The heavier vehicles without additional EMG power may not keep up with this speed profile in practice, because it belongs originally to a fully loaded tractor semitrailer (40t). For the heaviest vehicles in this study, road-load powers of up to 650 [kW] occur in these drive-cycles. The MEO simulation model allows for these high engine powers.
In a next stage of the project, these or other drive cycles should be made corresponding to the different vehicle types, such that the longer and heavier vehicles drive longer of the same route. This would however, also result in different driving times between the different vehicles, which further complicates comparison of results. Therefore, for this study it is chosen not to adapt the speed profiles to the vehicle and powertrain configurations. The Willans-line based powertrain models allow 'overloading', and simply will result in a higher fuel-rate when more power is requested. This will results in a somewhat optimistic result for the heaviest combinations.

3.6 MEO modelling extension

3.6.1 Original MEO model

The TNO in-house developed MEO modelling approach is based on a backwards vehicle model to derive from a drive cycle and vehicle specification the road-load power. This road-load power is the input to a Willans-line based powertrain model, to obtain a fuel consumption result.

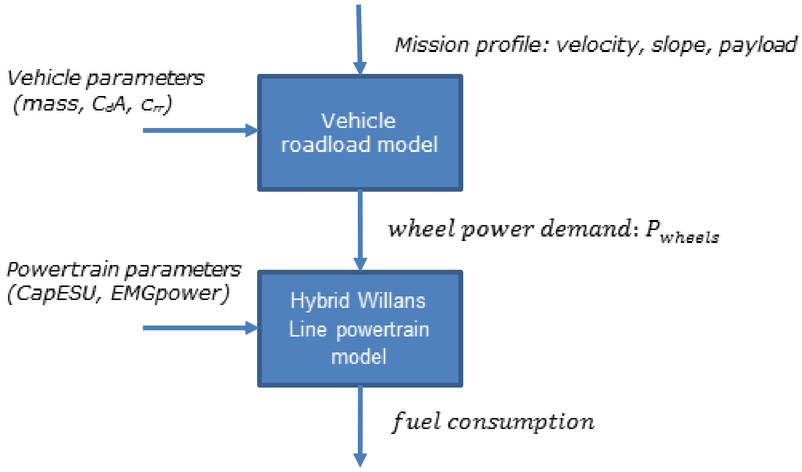


Figure 3 Structure of MEO modelling approach; consisting of a vehicle road-load model and a Willans-line powertrain model

The Willans-line model for the hybrid powertrain in the original MEO model, as was used in "AEROFLEX-WP2 Initial MEO Simulations Results-2018.03.23.pdf" (4) is illustrated in Figure 3. This model provides a mapping between drivetrain power and fuel-rate, and can be used to simulate a vehicle on a particular mission profile, to obtain the corresponding fuel consumption. For positive road-load powers, the drivetrain power is equal to the road-load power. The fuel-rate for positive drivetrain powers is given by the efficiency of the internal combustion engine and transmission; this implies that for positive drivetrain powers, the powertrain is modelled as a conventional, non-hybrid system.

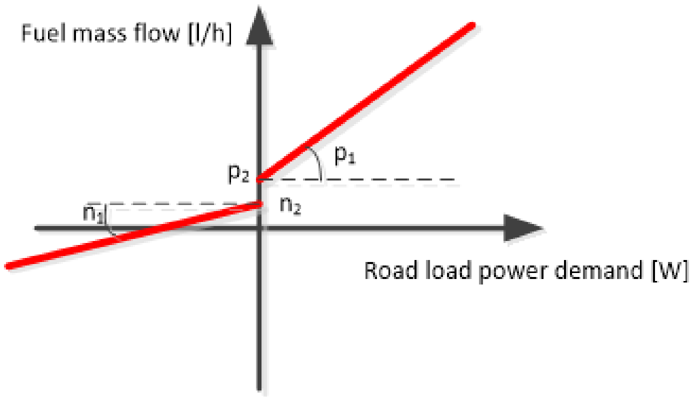


Figure 4 Illustration of the Willans-line model for a hybrid powertrain, used to calculate fuel consumption as a function of road-load power demand.

The effect of the hybrid system, consisting of the electric drive units in trailers and dolly, is accounted for through negative road-loads. During negative road-load periods, energy can be recuperated by the EMGs and stored in the battery. This energy can be used at a later time, to offset work by the internal combustion engine. Here, when negative road-load periods occur, an instantaneous reduction of fuel in assumed, whereas in practice this is stored and used a later moment in time.

3.6.2 Model extension

The MEO model is extended by replacing the hybridisation functionality described in the previous Section. In the extended MEO model, the effect of the electrical powertrain components is no longer limited as a fuel compensation due to energy recuperation. Instead, the electric powertrain components have a direct effect on the power that is demanded to the internal combustion engine. A simple battery model is added to secure that the energy storage limitation meets realistic constraints. The battery model is as follows:

$$P_s = P_b - \beta P_b^2$$
$$\dot{SOE} = \frac{P_s}{E_{s\_cap} \times 3600 \times 1000}$$

where
P_b [W]: Battery (dis-)charge at its terminal
P_s [W]: Battery net stored power
β [-]: Battery power conversion efficiency
E_{s_cap} [kWh]: Initial battery capacity
$\dot{SOE}$ [%/s]: Rate of change of State of Energy (SOE)

A simple, scalable power split controller is added to the MEO model. The implemented controller follows the approach proposed in (5). Figure 5 shows the different modes that the controller allows. The value of λ is determined by the power split controller. The variable λ represents the equivalent cost for electric power in [g/J].

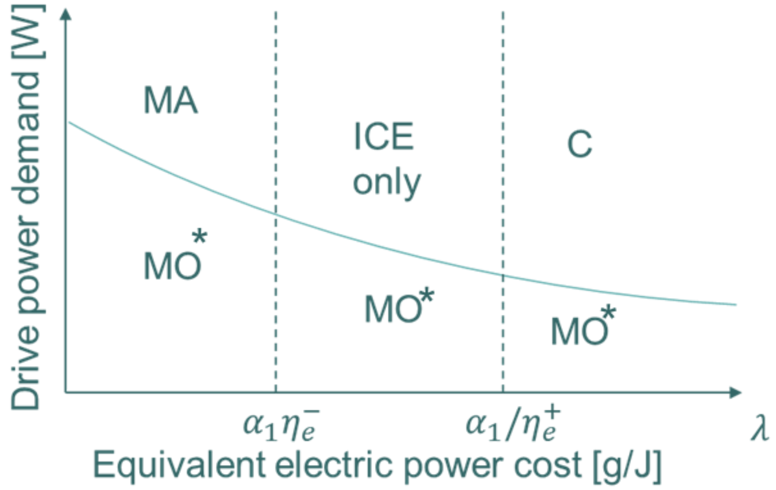


Figure 5 Hybrid modes allowed by the power split controller

The power split controller enables 5 different modes:

- **Charging while driving(C):** The internal combustion engine provides energy such that the battery can be charged. This can only occur if the engine is also used to propel the vehicle at the same time.
- **Internal combustion engine only (ICE only):** Only the internal combustion engine is used to propel the vehicle. The battery does not provide nor receive energy.
- **Motor assist (MA):** Both the internal combustion engine and the electric motor generator are used to propel the vehicle simultaneously. This mode uses energy from the battery.
- **Motor only (MO*):** Only the electric motor generator is used to propel the vehicle. The internal combustion engine is used only to power the auxiliaries. This mode uses energy from the battery.
- **Regeneration (R):** This mode occurs only when the demanded power from the powertrain is negative. In this mode, the battery is charged. If limits on the battery capacity or EMG are reached, the remaining energy is provided by the disc brakes. This mode is not displayed in Figure 5.

The power split controller is designed to perform charge sustaining, since the application considered is not a plug-in hybrid vehicle, allowing for charging via the grid. The input to the controller is the SOE error, defined as follows:

$$SOE_e = SOE_{ref} - SOE$$

The output of the controller is the equivalent cost for electric power λ. The control diagram is shown in Figure 6.

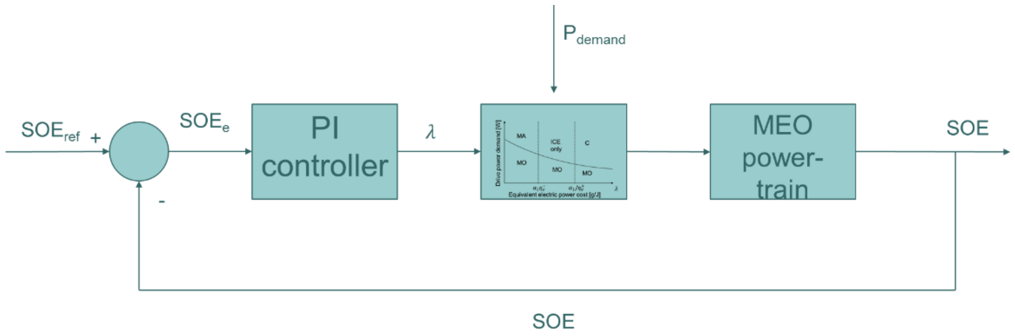


Figure 6 Diagram of the power split controller for hybrid systems

The assumptions underlying this modelling approach are detailed below:

- 'Perfect' brake-blending; all negative road-load up to EMG power limit is absorbed. Negative road-loads exceeding EMG power limits are provided by service brakes. Energy recuperation is thus EMG power limited;
- Hybrid-efficiency accounts for energy conversion losses;
- All EMGs are lumped into single total EMG power rating;
- Engine start/stop functionality is not considered; engine idling losses are always present; This assumption meets the actual configuration for the AEROFLEX Demonstrators. Due to the necessary operation of auxiliaries, the combustion engine cannot be stopped while driving.
- Reference SOE, SOE_{ref} is kept constant at 50%.

This modelling approach allows for a quick indication of the potential of fuel savings and is normally used for evaluation purposes. The current limitation is that it is always assumed that the mission profile is achieved with respect to speed and torque, providing an optimistic view. Regardless of the modelling limitations, the results are regarded as sufficiently accurate for the purpose of this study.

3.6.3 Additional vehicle parameters

The inclusion of the battery model and the power split controller requires additional parameters. These parameters are listed in Table 6. The original vehicle parameters presented in section 3.3 remain unchanged.

Table 6 Additional parameters of the electric powertrain components of the extended MEO model. The values are obtained from (7), part of EU-ORCA project

Electric powertrain parameter	Value
Battery power conversion efficiency β [-]	5e-7
C-rate [-]	20
Discharge & charge efficiency (combined EMG+Inverter) [-]	0.8
EMG power to weight conversion factor [kg/kW] *	1
Battery capacity to weight conversion factor [kg/kWh] *	8

3.7 Simulation test matrix

To correctly capture the effect of different levels of hybridisation for the defined vehicles, a large range of battery capacity and powers is explored for both the battery and the EMG, respectively. The simulation matrix includes the following variations:

- Vehicle configurations (tractor-semitrailer, EMS1, EMS2)
- Payload (empty, 20, 30, 40 tonne, full load)
- Mission profile (3 real-world routes from the EU Transformers project)
    - Flat highway, frequent elevations, mountain pass
- Different combinations of EMG and battery size. The explored values are shown in Table 7.

Table 7 Simulation matrix with respect to battery capacity and EMG power

Battery capacity[kWh]

Electric motorpower[kW]		1	5	10	20	30	40	50	60
	80	✓	✓	✓	✓	✓	✓	✓	✓
	160	✓	✓	✓	✓	✓	✓	✓	✓
	240	✓	✓	✓	✓	✓	✓	✓	✓
	320	✓	✓	✓	✓	✓	✓	✓	✓
	400	✓	✓	✓	✓	✓	✓	✓	✓
	480	✓	✓	✓	✓	✓	✓	✓	✓
	560	✓	✓	✓	✓	✓	✓	✓	✓
	640	✓	✓	✓	✓	✓	✓	✓	✓
	720	✓	✓	✓	✓	✓	✓	✓	✓

The coloured fields mark configurations at which the battery power (C-Rate =20) restricts the maximum power output of the electric drive. Simulations where no hybridisation is present are also performed to obtain reference performance values. Considering that the tractor semitrailer payload simulations can only go up to 26 tonne due to legal limitations for the NVW specified, and that the default vehicle is added for every case, a total of 2847 simulations were performed.

3.8 MEO simulation results

Savings of fuel consumption are presented in this chapter. In this context, fuel consumption refers to litre per kilometre [l/km]. The results are normalized against the conventional diesel vehicle without hybridization for the same vehicle type, payload and route as the corresponding figure. This means that the relative values based on l/km or l/tonne-km become equal. The results presented in this section include only the cases for 0 [%], 20 [t], and 100 [%] payload for readability purposes. The complete test matrix results including the 2 remaining payloads for the in this Chapter described results, are included in the Appendix A. Also the complete results of fuel consumption in [l/km] and [l/tonne-km], savings of fuel consumption of [l/km], and saving of fuel consumption of [l/tonne-km] are presented in Appendix A.

The results are depicted in the figures. Figure 7, Figure 8 and Figure 9 are for the different vehicle configurations, being tractor semi-trailer, EMS1 and EMS2, respectively. Each figure consists of in total 9 contour subplots in a 3x3 format. Each column represents the results for a given drive cycle, flat highway, frequent elevation changes, mountain pass, respectively. Each row corresponds to a particular payload.
Each contour plot horizontally shows the battery capacity [kWh] and vertically the EMG rated power [kW]. The contours show the fuel savings [%] compared to its own reference (conventional diesel) vehicle. Additionally, each contour plot contains of 2 optimum lines:

1) Minimum fuel consumption given a specified battery capacity;
2) Minimum fuel consumption given a specified rated EMG power.

The green dot in each contour plot, represents the numerical optimum in fuel consumption.

3.8.1 Tractor semitrailer

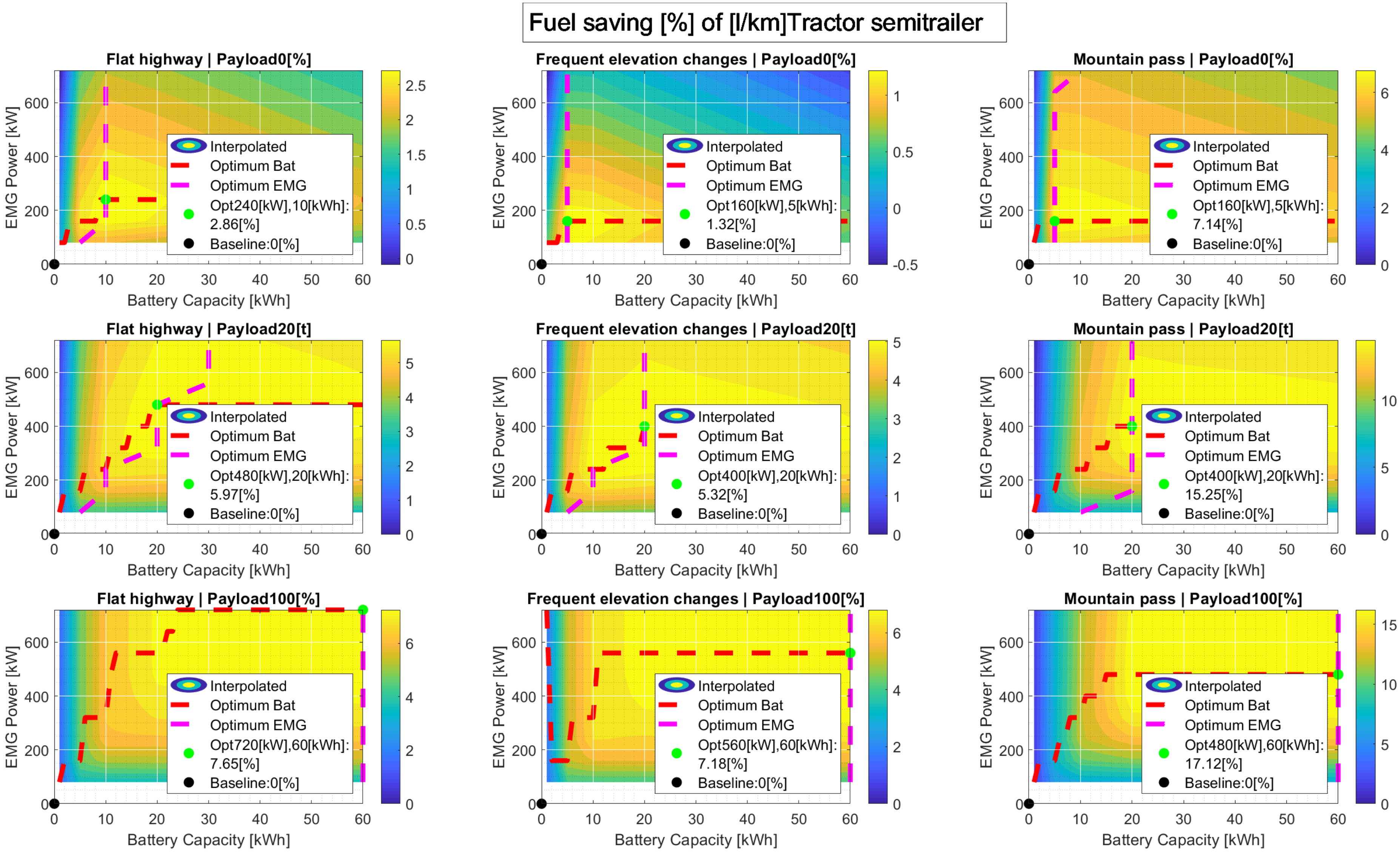


Figure 7 Saving [%] of fuel consumption in [l/km] for tractor semitrailer

3.8.2 EMS1

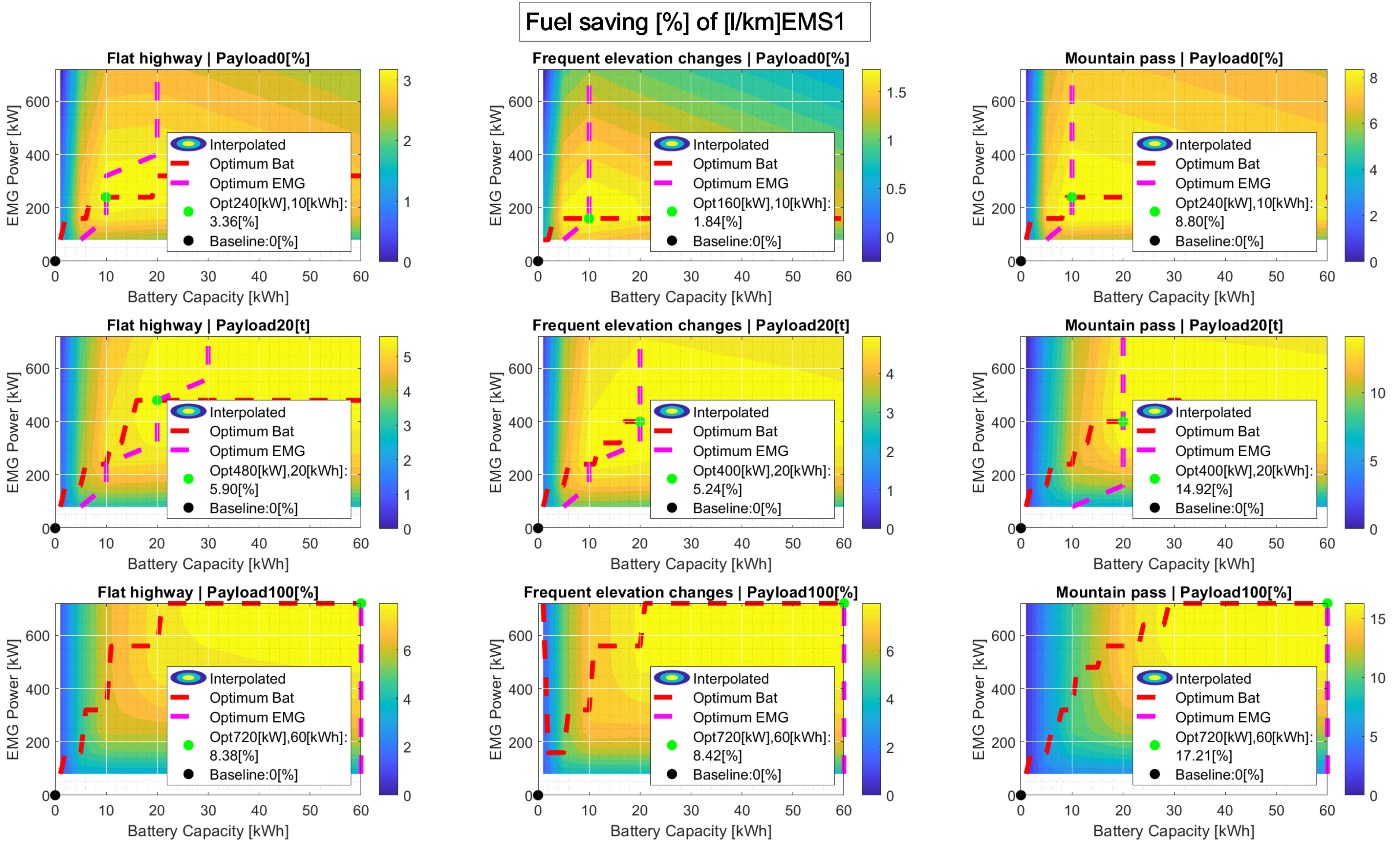


Figure 8 Saving [%] of fuel consumption in [l/km] for EMS1

3.8.3 EMS2

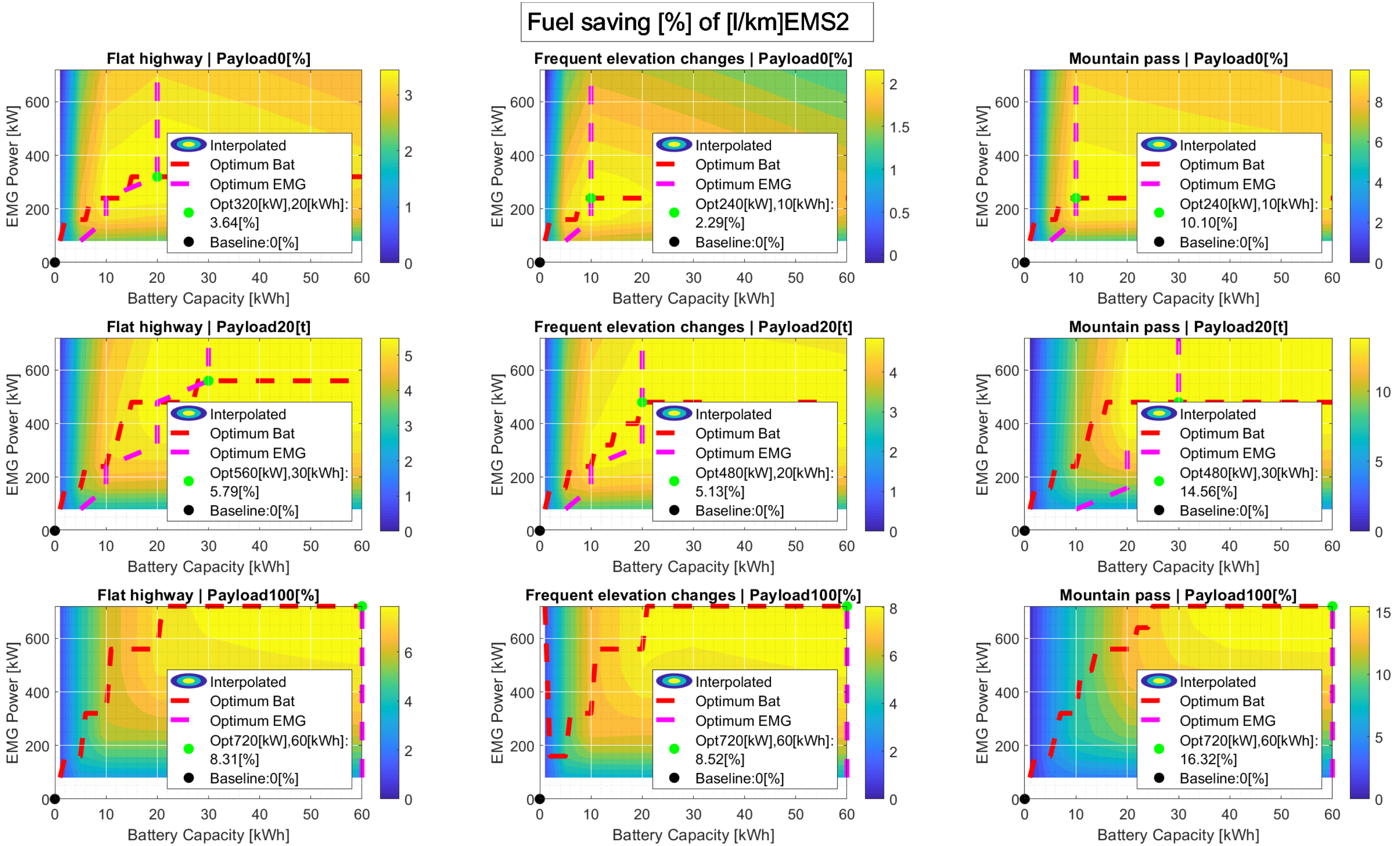


Figure 9 Saving [%] of fuel consumption in [l/km] for EMS2

3.9 Conclusions and recommendations

An extended MEO model is developed and applied to a hybrid component size study. The main trends are captured in the results (vehicle configurations, payload, energy demand, EMG/BAT sizing) in the basis of fuel consumption. There is a different optimum in EMG and battery sizing for each vehicle configuration, dependent on payload and application (drive cycle). However, the vehicle specific hybrid component sizes point towards:

- Tractor-semitrailer: 10-20[kWh] Bat, 180-300[kW] EMG , providing a fuel saving of 5-15[%] in l/km;
- EMS1: ~20[kWh] Bat, 240-400[kW] EMG , providing a fuel saving of 5-15[%] in l/km;
- EMS2: 20-40[kWh] Bat, 240-480[kW] EMG , providing a fuel saving of 5-15[%] in l/km.

The selection of the E-dolly components should support the compliance of the optimal configuration for both EMS1 and EMS2, which certainly is a compromise between the 2 vehicle types.
Further analysis and conclusions can be drawn from the results, but this is left to the reader to do.

3.9.1 Tractor semitrailer

Savings of fuel consumption in [l/km] in the range of 5-15 [%] compared to Tractor-semitrailer with conventional powertrain are obtained. The suggested electric powertrain configuration considers, dependent on application (drive cycle) and payload:

- Battery: 10-20 [kWh]
- EMG: 160-300 [kW]

Table 8 Recommended electric components for tractor semitrailer

	Flat Highway	Frequent elevation changes	Mountain pass
20 [t]	Bat=20[kWh] EMG≥240[kW]	Bat=15[kWh] EMG:≥320[kW]	Bat=20[kWh] EMG≥400[kW]
100[%]	Bat=10[kWh] EMG≥160[kW]	Bat=10[kWh] EMG≥160[kW]	Bat=15[kWh] EMG≥400[kW]

3.9.2 EMS1

Savings in the range of 5-15 [%] compared to EMS1 with conventional powertrain are obtained. The suggested electric powertrain configuration considers:

- Battery: ~20 [kWh]
- EMG: 240-400 [kW]

Most of the scenarios show a 20kWh battery capacity being optimal, except for the fully loaded EMS1 at the mountain pass. In that case, a larger battery is more optimal, 30kWh.

Table 9 Recommended electric components for EMS1

	Flat Highway	Frequent elevation changes	Mountain pass
20[t]	Bat=20[kWh] EMG≥240[kW]	Bat=20[kWh] EMG≥240[kW]	Bat=20[kWh] EMG≥320[kW]
100[%]	Bat=20[kWh] EMG≥240[kW]	Bat=20[kWh] EMG≥240[kW]	Bat=30[kWh] EMG≥400[kW]

3.9.3 EMS2

Savings are in the range of 5-15 [%] compared to EMS2 with conventional powertrain. The suggested electric powertrain configuration considers:

- Battery: 20-40 [kWh]
- EMG: 240-480 [kW]

Table 10 Recommended electric components for EMS2

	Flat Highway	Frequent elevation changes	Mountain pass
20 [t]	Bat=20[kWh] EMG≥320[kW]	Bat=15[kWh] EMG≥240[kW]	Bat=20-30[kWh] EMG≥400[kW]
100[%]	Bat=10[kWh] EMG≥320[kW]	Bat=10[kWh] EMG≥240[kW]	Bat=40[kWh] EMG≥480[kW]

3.10 Outlook

New loading optimisation strategies will be developed within the AEROFLEX project. The assessment of these strategies will require the inclusion of new indicators to the MEO simulations. It is expected that [% fuel saving/m^{3}km] will be an additional indicator with special attention during these MEO simulations. This special focus will also include the assessment of fuel efficiency in [l/tonne-km].

Due to the different vehicle configurations, the speed-time profiles will be different, which will be included in the final assessment work and consequently lead to different trip durations, so average vehicle speed need to be considered as additional KPI.

Further analysis of the impact of different battery capacities would be beneficial for the design of hybrid powertrains. The study can be extended on the following topics:

- Cyclic behaviour of HOD strategy and its fuel consumption
- Reference SOC variations, preview information usage
- Sensitivity analysis on EMG/BAT weight functions and powertrain efficiencies

Detailed Simulations in a MAN simulation environment will follow as soon as all components are chosen and functions are ready. These detailed simulations will take into account:

- The sophisticated energy management system which will be present in the demonstrators
- Separate electric drives
- Detailed efficiency maps for powertrain components like the combustion engine or electric motors
- Dynamic behaviour of the combustion engine
- Torque restrictions to the electric motors given by an vehicle dynamics controller which ensures a stable operation
- Tire slip
- Vehicle functions as predictive cruise control
- Influence of available drive power and vehicle weight on speed profile (forward simulation)

3.11 Requirements to the AEMPT and KPIs

AEROFLEX aims to reduce fuel consumption of AEMPT vehicles up to 12% by powertrain technology. The simulation results presented above show that such a high value may only be achieved with a high electric power rating on a suitable cycle. Of course a sophisticated energy management may improve results, but real world behaviour of powertrain components may also make results worse. In any case, only the optimum configuration of electric drive components will enable reaching to efficiency target. In order to derive general requirements for EMG power and battery capacity from the simulation results, only the Flat Highway cycle and the Frequent Elevation Changes cycles are taken into account. The Mountain pass is not regarded as a typical route for EMS vehicles. From the suggested ratings for battery capacity and EMG-power for fully loaded vehicles, values per ton GCW of 4kW/ton EMG power and 0,35kWh battery capacity/ton can be derived. In summary, the energy demand requirements and accordant KPIs are:

Table 11 Energy and Power Requirements to the AEMPT

Index	Dependent from Index	Category	Requirements	Comment/KPIs
ED - 1		Energy/Power Demand	The battery capacity and electric power of an AEMPT vehicle shall allow efficiency improvements of 12% for AEMPT vehicles	KPIs: Fuel Consumption per 100km, Fuel Efficiency per ton-km, Average Speed
ED -2	ED - 1	Energy/Power Demand	The overall battery capacity shall be not less than 0,35kWh/ton GCW	
ED -3	ED - 1	Energy/Power Demand	The overall EMG power shall be not less than 4kW/ton GCW	

The KPIs Fuel Consumption per 100km and Fuel Efficiency in ton-km have been explained at the beginning of this section. Additionally, the KPI Average Speed has been added in Table 11. This KPI is very relevant for assessing fuel consumption because a direct comparison of fuel consumption is only valid for similar average speeds in a specific cycle.

4 Energy Management

4.1 General Requirements

The energy management shall ensure that the combustion engine and electric drives act together as efficient as possible. This is the main requirement to the energy management. The efficiency of a hybrid system is basically defined by the ability to recuperate energy when braking and by using this collected energy in an efficient manner. Herein, using energy means requesting accelerating torque from electric machines. For maximum fuel savings, electric torque should be requested in a way that allows the combustion engine to run in efficient operating points. Of course, additional electric power may be used to achieve a higher speeds on high power driving situations like upward slopes. However, as improving energy efficiency is the major goal of AEROFLEX, the energy management shall not operate the drive units in a way which increases average speed on relevant cycles.

Of course, in line with the basic ideas of AEROFLEX, the energy management shall allow to flexibly combine vehicle units. This means that the energy management has to flexibly adapt to a new vehicle configuration if vehicle units are coupled or uncoupled. As an example, the energy management system has on one hand to efficiently operate a tractor-e-Semitrailer Configuration including an electric drive in the trailer. On the other hand, if an e-Dolly and another Semitrailer is coupled to the vehicle, extending it to a EMS2 configuration, the energy management has to efficiently operate also that combination.

In section 2 it has been explained, that an AEMPT vehicle may include up to four trailer units. Assuming that each trailer unit is equipped with one electric drive and there is also an electric drive in the pulling unit, the energy management shall be capable of managing one combustion engine in combination with up to five electric drives.

Besides energy efficiency, also driver comfort has to be taken into account, as it is crucial for acceptance of a product. Therefore, as a further general requirement, the energy management shall operate the drive units in a way which does not feel uncomfortable to a driver. This might result in limits to torque gradients which have to be parametrized during test runs of the vehicle.

Of course the energy management system has to interact with existing systems in a vehicle. Examples are features like predictive cruise control or the EBS systems. Therefore, as a general requirement, the energy management system has to properly act together with existing systems in a truck.

4.2 AEMPT Architecture

Central vs. decentral system

The AEMPT will integrate multiple vehicle units which bring their own driveline. An architecture of a powertrain control system could be set up in two very different ways:

1. A centralized system having one global controller and multiple local controllers in a master slave dependency.
2. A decentralized system where each drive unit takes its own decisions.

A centralized system would use data from the local controllers to find an optimized way of operation for the overall system. Such an approach would strongly account for the goal of reaching high fuel savings. However a decentralized system might be more flexible. Such an approach which is closer to the concept of the Transformers project requires less communication among the vehicle units. This facilitates the task of creating a standardized communication protocol. But of course, flexibility can also be provided by a centralized system if enough effort is put in designing a suitable interface. A third aspect to consider in this question is safety of the vehicle. As seen in section 3, the electric drives should have a power rating of several hundred kWs for EMS vehicles in order to reach efficiency goals. In section 5 it will be highlighted that such strong drives in a dolly or trailer can have significant influence to vehicle stability. To guarantee a safe operation of the combination, a centralized system is advantageous because it can combine all information to a consistent stability control. However, as can be seen in state of the art trailer EBS systems, there might also be a sufficient decentralized solution. The following table summarizes advantages/disadvantages of the concepts.

Aspect	Centralized control	Decentralized control
Energy efficiency	+	-
Flexibility	o	+
Safety	+	-

Table 12 Centralized vs. decentralized powertrain control system (+/-/o : positive/negative/neutral)

After a detailed discussion in an early project phase the WP2 partners decided to go for the centralized system. As energy efficiency is the most important project goal, this aspect outweighs a possibly advantage in flexibility.

Global Energy Management, Local Controllers and Communication

A centralized energy management system is made up from a global energy management in the pulling unit and local controllers in the trailer units. The global energy management will also be referred to Global Energy And Torque Managements System (GETMS). A local controller will be referred to as Local System Management (LSM) The GETMS will collect data from LMS instances and find an efficient way of operating the drive units. As example, the LMS instances will send information about a currently available power of an electric drive and the GETMS will request a certain share of it. Accordingly, each LMS has to send relevant data to the GETMS.

What data in detail is sent and received by the controllers will be defined in a communication protocol as part of D2.2 Accordingly, as a communication requirement, the communication interface should allow integrating multiple vehicle units. According to the vehicle portfolio, an AEMPT vehicle may include up to four trailer units. Figure 10 depicts the energy management concept based on the basic requirements outlined above.

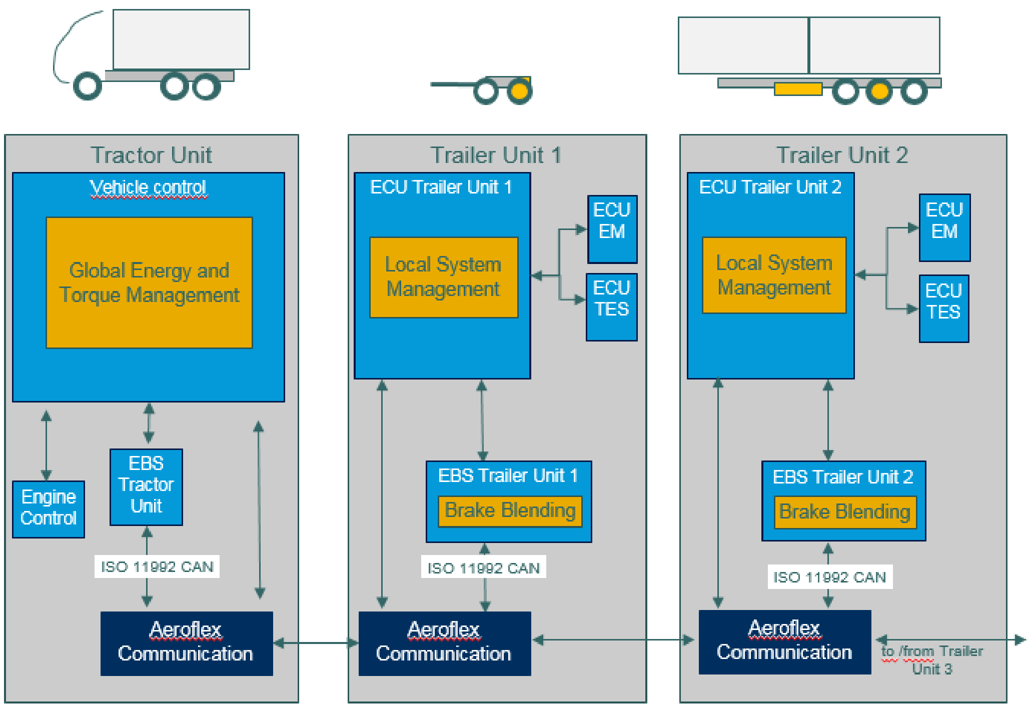


Figure 10: Energy Management Structure

HV-connection between vehicle units

Another important question is whether the vehicle units should be connected by a High Voltage (HV) connection. A HV connection would allow transferring energy between the drive systems. This could be useful if e.g. the truck has a HV-System and energy should be stored in a large trailer battery in a recuperation phase, if there is no more capacity in the truck battery. However, there are several strong arguments which stand against an HV-connection:

- Connecting HV-systems of different vehicle units is not possible without additional DC-DC-convertors. Separate HV-systems will always have differences in their voltage levels because of battery configuration and battery state of charge. If such systems, e.g. of a truck and a trailer, are simply plugged together a short circuit is created. A technical solution for this problem are DC-DC converters which raise costs and complexity of the overall system.
- If each drive unit is designed well, the number of situations which allow sharing of energy will be small. In the AEMPT concept, vehicle units like a dolly or a trailer can bring their own electric drive including a battery and an electric motor. In order to be able to flexibly connect vehicle units each vehicle unit for itself should be designed in a way that the battery suits the power rating of the electric motor. Accordingly there will seldom be the need or possibility to share energy. As an example, in a strong recuperation phase, the battery of a vehicle unit will not be able to receive additional energy from other vehicle units. Otherwise this battery has a too high power rating looking at this particular vehicle unit.
- In terms of energy efficiency, transferring energy from one HV-system to another is always unfavourable compared to using the energy in an electric motor within the same HV-system. This is because of power losses in DC-DC convertors and resistances of cables.
- Transferring energy between HV-systems is also possible without HV connector “through the road”. This state can be realized by putting one electric drive in generator mode while another drive system (e.g. the combustion engine) compensates for this additional drive resistance. Of course the efficiency of distributing energy this way is less that distributing it via HV-connectors. However, as it will be seldom efficient or necessary to transfer energy anyway, the overall effect to fuel consumption of this approach can be assumed to be very limited.
- HV-connections between the vehicle units would also greatly reduce the flexibility of the AEMPT architecture, because the HV-connections and even the HV-system layouts of the vehicle units would have to be standardized to quite a high degree. E.g., the voltage levels of the HV-systems in all vehicle units would have to be standardized to enable a connection between the trailers. Of course, the HV-plugs and –cables would also have to be standardized. Moreover, the method for the insulation measurement of the whole HV circuit in coupled state would have to be aligned between manufacturers of the pulling unit and the trailers.

Looking at this reasoning, the decision of not considering HV-connectors in the AEMPT is obvious. Of course there are other applications where such connections can make sense. E.g. transferring energy from a HV-generator on a tractor unit to a cooling device on a trailer. However such applications are out of scope of this project which looks at flexible EMS vehicles.

4.3 Outlook

Based on the findings presented above, the development of energy and torque management functions have already started. The functions will be integrated in a detailed virtual vehicle model. Virtual cycles will be simulated to validate the concept and to find suitable parameters. Also the interaction of the global energy management and local controllers will be virtually tested. Details on the energy management implementation will be presented in D2.2.

4.4 Requirements to the AEMPT and KPIs

Table 13 sums up the energy management requirements to the AEMPT:

Table 13 Energy Management Requirements to the AEMPT

Index	Dependent from Index	Category	Requirements	Comment/KPIs
EM - 1		Energy Management	The energy management shall operate the drivetrain components efficiently to allow for high fuel savings	KPIs: Fuel Consumption in l/100km, Fuel Efficiency in l/ton-km

EM – 2	EM - 1	Energy Management	The energy management shall enable to recuperate as much energy as possible	
EM – 3	EM - 1	Energy Management	The energy management shall request torque from the electric drives in a way that allows the combustion engine to run in an efficient operating point	
EM – 4	EM -1		The energy management shall not operate the drive units in a way which increase average speed on relevant cycles	KPIs: Average Speed
EM – 5		Energy Management	The energy management shall be able to flexibly adapt to different vehicle configurations	
EM – 6	VP - 1	Energy Management	The energy management shall be able to take into account one combustion engine in combination with up to five electric drives	
EM – 7		Energy Management	The energy management shall efficiently work together with existing systems in a state of the art truck	
EM – 8		Energy Management	The energy management architecture shall have a centralized structure	
EM – 9		Energy Management	The energy management architecture shall consist of a global energy and torque management system (GETMS) and local system management (LSM) instances in the trailer units.	
EM – 10		Energy Management	Each LMS shall provide information according to an AEMPT protocol to the GETMS.	
EM – 11	VP - 1	Energy Management	The communication interface should allow integrating up to five vehicle units	
EM – 12		Energy Management	An HV connector shall not be part of the AEMPT Architecture	
EM - 13		Energy Management	Applying electric torques shall not lead to an uncomfortable feeling of the driver	

5 Vehicle Dynamics

5.1 General Requirements

In this section, vehicle dynamics requirements for AEMPT vehicles are outlined. The focus is put on high speed stability and driveability. As a very basic requirement, an AEMPT vehicle shall dynamically not perform worse than EMS vehicles without electric drives.

Regarding high speed stability, there obviously cannot be made any compromise. Extensive operation of long and heavy vehicles in countries as Australia and Sweden have proven, that these vehicles are not less safe than conventional shorter vehicles (7). Therefore, fulfilling the same safety standards as conventional EMS vehicles is regarded as a reasonable requirement. Moreover, as will be explained in the following section, new criteria are added in order to take into account the effect of additional electric drives.

When it comes to drivability, electrically driven axles can show big advantages in terms of traction and acceleration capability. As there will be additional costs for such axles, an improved drivability can be one argument for logistic companies to operate these vehicles.

For conventionally driven EMS vehicles, FALCON (2) has extensively investigated stability and driveability requirements mainly based on the Australian PBS. In line with the general requirement to perform not worse than conventional EMS vehicles, the findings of FALCON will be applied as far as possible.

In FALCON (2), the PBS thresholds are defined depending on the applicable road class. In line with Australian PBS thresholds are defined depending on road classes 1 to 4. For European roads, FALCON regards level 2 thresholds as suitable for EMS vehicles up to 25,25m (EMS1). For longer vehicles (EMS2), level 3 thresholds are regarded as applicable. As a rather strict assessment, level 2 thresholds will be applied for all AEMPT vehicles. Of course, before operating a vehicle on a specific route, the applied threshold level has to match the specific infrastructure.

5.2 Lateral Vehicle Dynamics

Including additional driven axles in an EMS vehicle, in particular into a dolly or a trailer may cause unwanted dynamic behaviour of the vehicle. This chapter explains what requirements an AEMPT vehicle should fulfil in order to allow a safe operation. Based on this analysis, a vehicle dynamics controller will be developed which accordingly restricts output torques of the electric axles.

To develop and adjust this vehicle dynamics controller, KPIs need to be identified which must be met by AEMPT vehicles. These KPIs shall cover driving situations that may lead to critical situations. Virtual tests in the development phase and on-road test in the later stage will allow to determine whether safety thresholds of the identified KPIs are met.

For conventional powertrain high capacity vehicles there is already a large knowledge base for such KPIs which are also referred to as Performance Based Standards. In particular, it is referred to Australian PBS (8) and the findings of the FALCON project (2).

5.2.1 Simulation Environment

To understand and assess the behaviour of AEMPT vehicles in different driving situations, a suitable simulation approach has been set up. Due to the complexity of this topic and also for safety reasons, investigating vehicle dynamics only on test tracks is hardly feasible. Moreover, in this stage of the project, no demonstrators exist yet to be assessed on test tracks.

The simulation environment consists of multi-body vehicle models set up in the software package SIMPACK. The models can be run on different tracks respectively in different driving scenarios. Control algorithms will be designed in MATLAB/Simulink and coupled with the vehicle model. Different multibody models have been created for different purposes. At this stage three different model stages are used:

- Single track model for the qualitative assessment of vehicle dynamics.
- Dual track model using simplified axle models and rigid bodies only for the quantitative assessment of vehicle dynamics (Performance Based Standards). The axle models used comprise only a vertical and rolling degree of freedom.
- Detailed vehicle models for the assessment of the self-steering behaviour, see Figure 11. In this case, elastokinematic axle models (Figure 12) and flexible frame models are used.

Figure 11 Detailed vehicle model of EMS1 vehicle combination in a cornering scenario

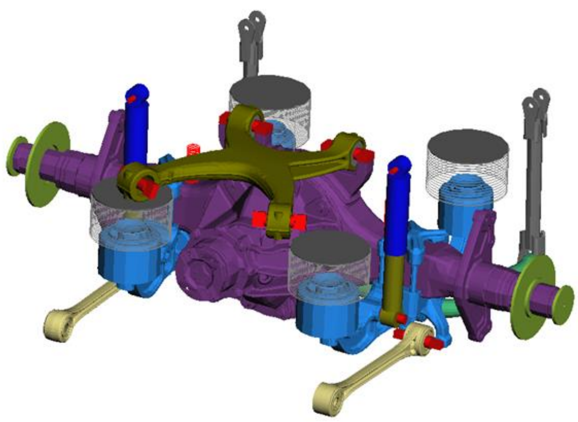


Figure 12 Elastokinematic drive axle model of the towing unit in Figure 11

5.2.2 Simulation Results

5.2.2.1 Yaw Damping Coefficient for AEMPT vehicles

The yaw damping coefficient, defined in Australian PBS is a very important measure for high speed vehicle stability (damping of sway oscillations. It can be expected that effects of the electric drives can be well observed in this manoeuvre, so it has been selected as a starting point. In this manoeuvre a steer impulse is applied on the front axle of the towing unit. The relevant measure is the decay rate of the combination's articulation angles.

The dual track model described in section 5.2.1 has been used in order to calculate the yaw damping coefficient for a 25 m EMS1 configuration according to the AEROFLEX Demo vehicle.

The model and scenario setup has been chosen as follows. The model has been configured according to the accordant Australian PBS manoeuvre.

- Dual track model for EMS1 (Figure 13)
- Truck and trailer are loaded (truck 25.8 t, dolly and trailer together 36.1 t)
- v = 80 km/h
- Steer impulse according to Australian PBS > a_{yH} at front axle is 2 m/s²
- Tire-road friction coefficient is 0.8 (standard asphalt at dry conditions, TMeasy tire model)
- Drive torque applied at truck rear axle or dolly drive axle (default/reference condition) or dolly drive axle (worst-case, full electric drive)

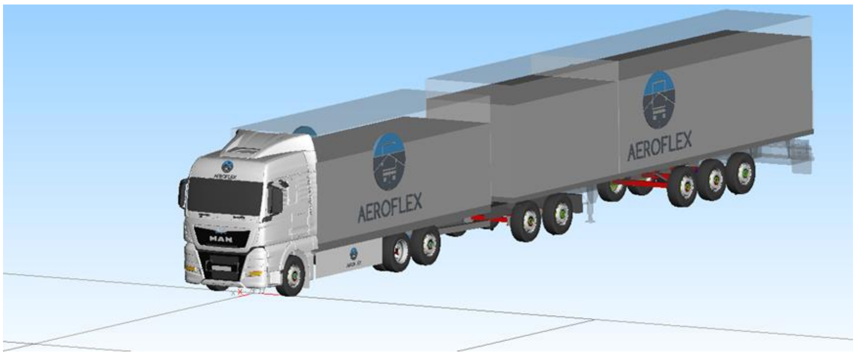


Figure 13 Dual track model of EMS1 vehicle combination for calculating the yaw damping coefficient

Figure 14 shows the articulation angle time histories of the dolly and of the trailer respectively. The black and red line represent the conventional driving scenario (drive on rear axle of the towing unit), whereas the green and blue lines represent a scenario where the whole propulsion force for the combination is delivered by the second dolly axle. In the current example the dolly motors deliver a power of about 120 kW to maintain the vehicle speed against air drag and rolling resistance.
The yaw damping coefficient is calculated by using the oscillation amplitudes of the articulation angles (Figure 15). In this case, the kingpin angle is used since it has the lower damping. In case of conventional driving the yaw damping coefficient is 0.25. According to the standard the value should be above 0.15.
Consequently, considering Figure 14 no significant change in the yaw damping coefficient is to be expected in case of driving the dolly. The time histories are almost equal for both driving modes.

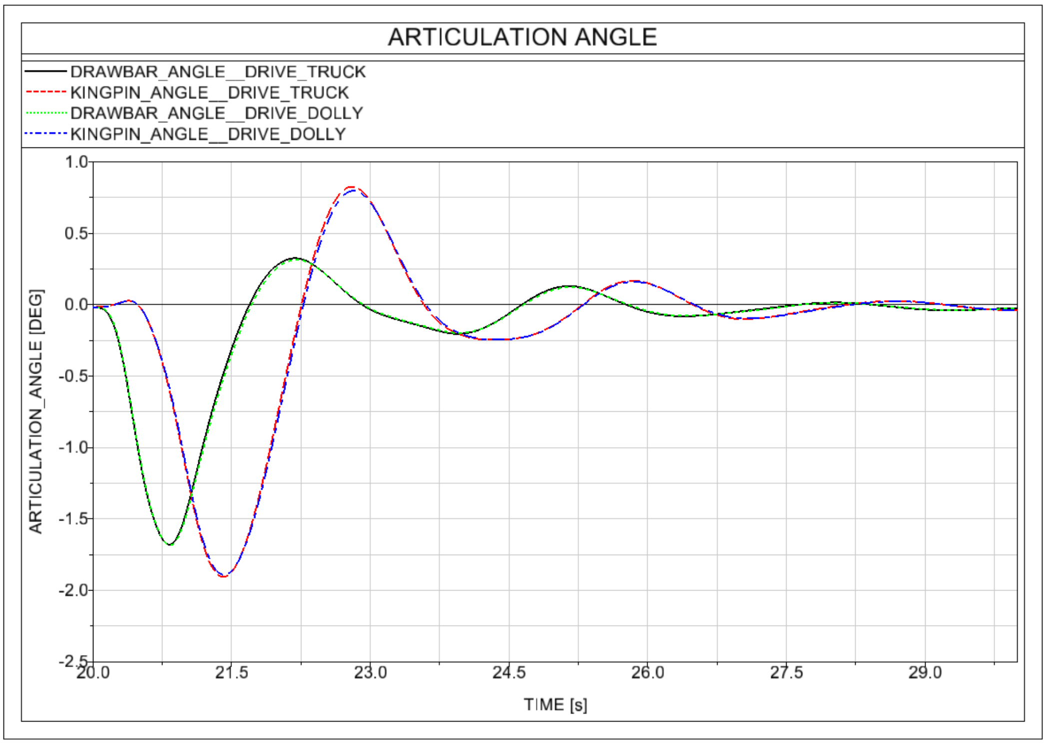


Figure 14 Time history of articulation angles in case of conventional or electric driving

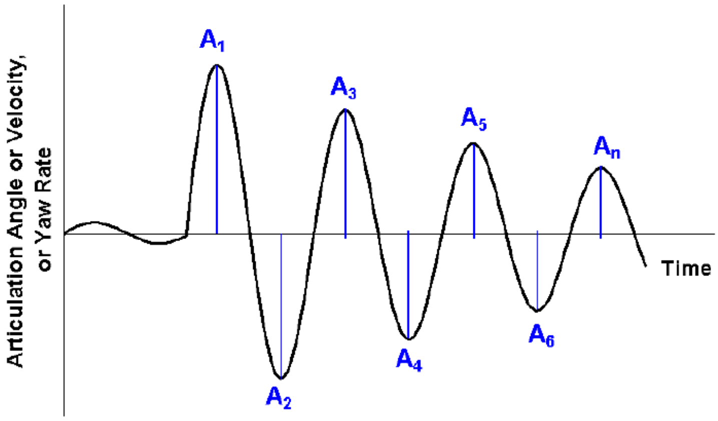


Figure 15 Amplitudes of articulation angles used for calculating the yaw damping coefficient (8)

The situation is different if a low tire-road friction is used (μ = 0.5) and if the steering impulse is applied during full power acceleration (In the standard PBS the manoeuvre is carried out with constant velocity). Figure 16 shows that in this case the sway oscillations are significantly higher in case of driving the dolly. The articulation angles at the drawbar joint (black curve) and the kingpin (red curve), both for the conventional driven truck, are considerably smaller than the articulation angles at the drawbar joint (green curve) and the kingpin (blue curve) for the electric drive torque at the dolly axle.

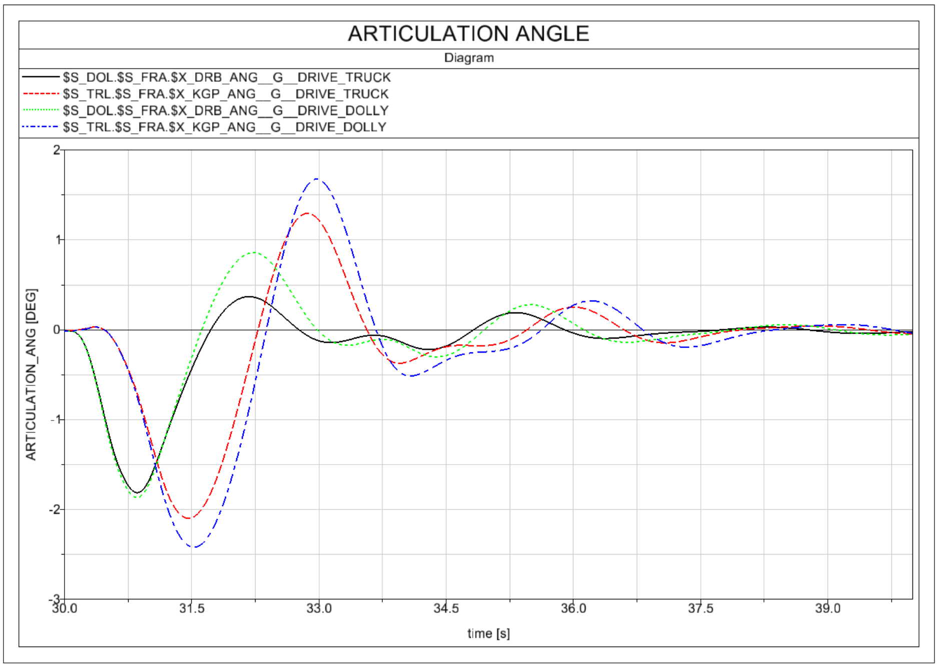


Figure 16 Time history of articulation angles in case of conventional or electric driving, μ = 0.5 and full power acceleration

This simulation has shown that standard PBS have to be modified or new criteria have to be developed in order to show and assess the effects of driving towed units in the combination. Without the modification of the given standard, the differences between the vehicle variants would not have been detected. In addition, new scenarios and standards have been defined with the particular focus on driving towed units. First simulation results for a new scenario are depicted in the following subsection.

5.2.2.2 Recuperation Scenario during Cornering

The installation of high power electric motors on different axles of the towed units lead to changed lateral dynamics of the combination especially when driving/braking torques are applied during cornering. This is because drive or braking forces in the road-tire contact reduce the lateral guiding potential. Hence, an AEROFLEX scenario has been defined to assess the effect of recuperation on a towed unit during cornering. The simulations show that both the magnitude of the recuperation torque and the rate of torque change (torque gradient) has significant effects on the lateral dynamics of the combination.

The simulation setup is described in the following:

- Dual track model for EMS1
- Truck is unloaded (vehicle weight 11.3 t), dolly and trailer are loaded and weight together 36.1 t)
- Tag axle is lifted
- v = const. until recuperation
- Friction coefficient is 0.8
- Constant cornering (constant steer angle) followed by a drivetrain shutoff on the truck and switching on the recuperation on the dolly

Figure 17 shows the required drive torques on wheel level (dashed lines) to keep the vehicle at a constant speed during cornering. At about t = 35 s the drive torque is ramped to zero and a recuperation torque (solid lines) is applied to the dolly. The different line colours represent different gradients for shutting off the drive torque and switching on the recuperation torque. The torque gradient range is between 16 kNm/s and 2 kNm/s.

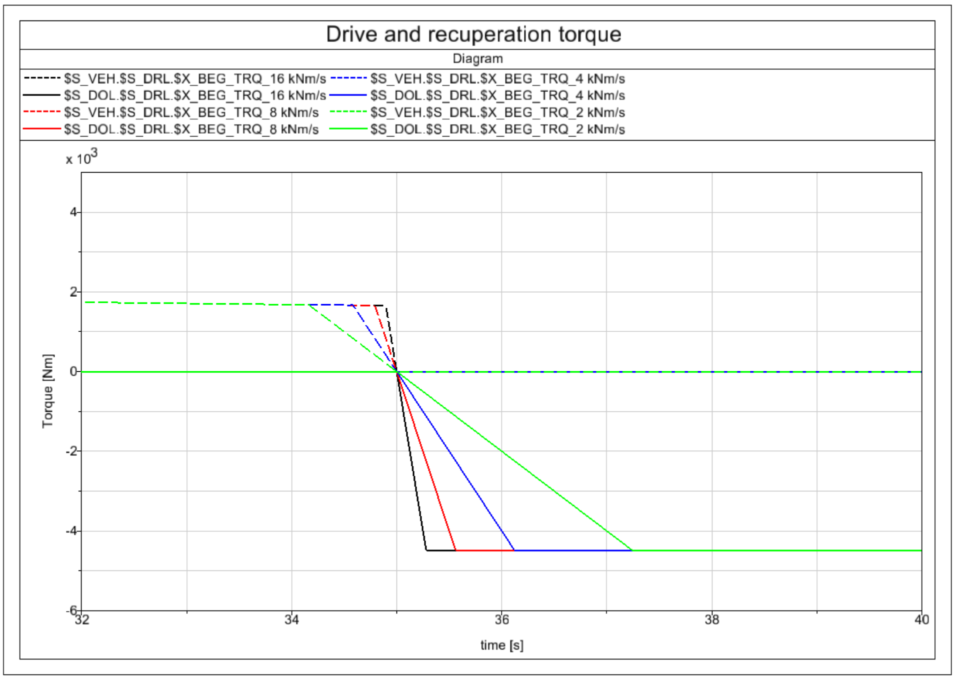


Figure 17 Drive and recuperation torques of the vehicle combination using different torque gradients

In Figure 18 the dynamic response of the towing vehicle and the dolly is shown for the different torque gradients. It is obvious that high torque gradients lead to high dynamics on the dolly (sway oscillation). In the given diagram the yaw rates of the towing vehicle and the dolly for different recuperation torques are shown. With increasing recuperation torque the dolly shows higher yaw rates.

This also applies to the lateral displacement of the trailer in this scenario. The lateral displacement shown in Figure 19 is the displacement of a point on the trailer centre axle in the front plane with regards to an imaginary point fixed to the towing vehicle, which is in the same position in case of a complete straight vehicle combination. Hence, this measure is a quantity for the lateral swing out of the trailer front. The time history shows that the lateral displacement is approximately 3 cm in case of steady state cornering and can reach up to 10 cm in the first phase of recuperation in case of a high torque gradient. In case of a low torque gradient the lateral displacement is below 5 cm.

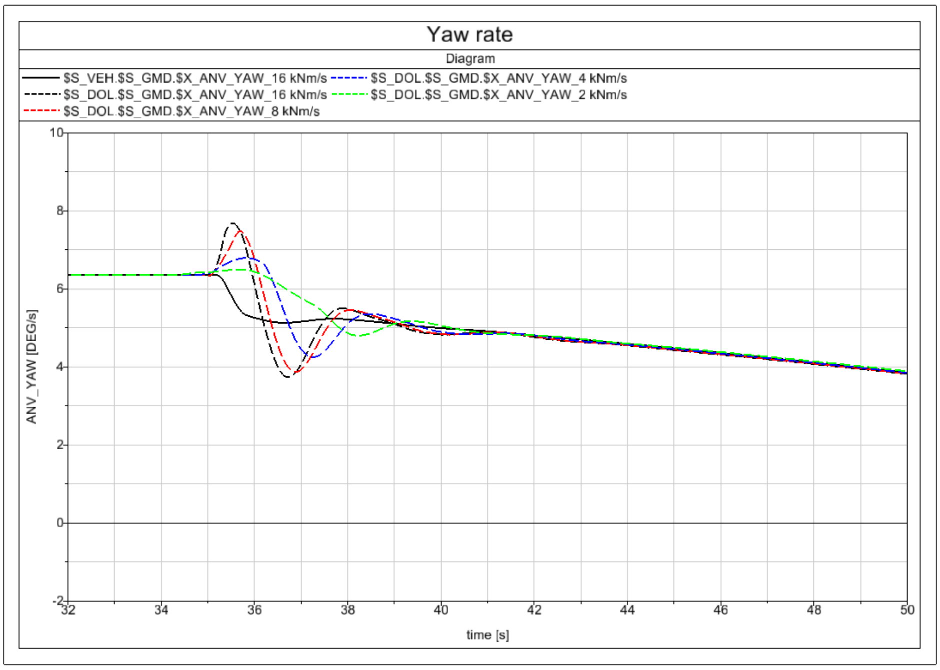


Figure 18 Time history of yaw rates for the towing vehicle and the dolly using different torque gradients

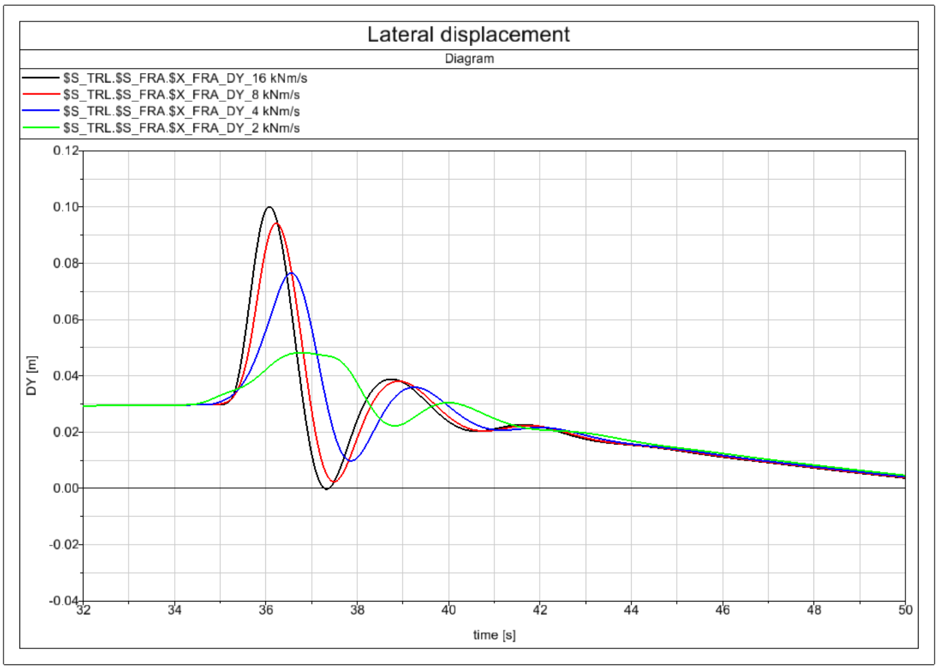


Figure 19 Lateral displacement of the trailer front with respect to an imaginary point of the towing unit, which is in the same position in case of a completely straight vehicle combination

It is obvious that high torques and/or high torque gradients may lead to unacceptable vehicle performance with regards to yaw rates or lateral displacements. Therefore, additional manoeuvres have to be defined with account for such influences.

5.2.3 Extended PBS for AEMPT vehicles

The results of the dual track model used in standard PBS scenarios have shown that there is no significant difference in lateral dynamic behaviour if the combination is driven conventionally or in electric mode. This can be explained by the effect that the driving forces are moderate in the lateral dynamics tests and that the tire-road friction is assumed to be high (μ = 0.8). However, for a lower friction or higher torque values it is obvious that differences between conventional and electric driving mode are not neglectable. In addition, simulations show that recuperating in a curve, especially at axles in towed units, by can have high effects on the lateral vehicle stability. Hence, from an AEROFLEX point of view the standard PBS have to be modified and additional standards have to be defined.

Accordingly, the following additional manoeuvres to assess AEMPT vehicles are suggested.

- STEERING ANGLE GRADIENT: Constant radius at defined speed and friction, followed by a recuperation event. The vehicle behaviour can be evaluated in terms of yaw rate, lateral displacement and lateral acceleration.
- CORNERING STABILITY UNDER ACCELERATION: Constant radius at defined speed and friction, followed by an accelerating event. This manoeuvre is analogue to the one mentioned before except the torque direction and of course the possible vehicle reaction.
- CORNERING STABILITY UNDER DECELERATION: Constant radius quasi-steady turn to assess the steering angle gradient for different torque distributions.

Detailed parameters (such as radii, cornering angles for example) of these scenarios will be defined within the course of work.
A table with the current work status of the so far defined criteria and manoeuvres is given below. The already existing manoeuvres are also included.

KPI	Threshold	Source	Purpose
TRACKING ABILITY ON A STRAIGHT PATH	Level 2: 3 m	Australian PBS C5	ensure that vehicle stays in its lane in spite of stimulations
STATIC ROLLOVER THRESHOLD	all levels > 0,35 g	Australian PBS C11	limit rollover tendency during steady turns
REARWARD AMPLIFICATION	not greater than 5.7 times the static rollover threshold of the rearmost unit (all levels).	Australian PBS C12	limit the lateral response of multi-articulated vehicles during avoidance manoeuvres without braking
HIGH-SPEED TRANSIENT OFFTRACKING	Level 2: Trailer lateral overshoot not greater than 0.8 m	Australian PBS C13	limit the sway of the rearmost trailer during avoidance manoeuvres at highway speeds
YAW DAMPING COEFFICIENT	Not less than 0.15 at the certified vehicle speed for all levels.	Australian PBS C14	require acceptable attenuation of any sway oscillations of rigid vehicles
DIRECTIONAL STABILITY UNDER BRAKING	Level 2: 0.35 g within a lane width of 3.0 m	Australian PBS C16	manage safety risk of vehicle instability when braking in a turn or on pavement cross slopes.
STEERING ANGLE GRADIENT.	Steer angle gradient for differen load conditions and torque distributions in defined interval (tbd.). Interval definition according to conventional EMS.	Driving Dynamics basic test procedure: Constant radius quasi-steady turn.	examine over- or understeering tendency
CORNERING STABILITY UNDER ACCELERATION.	tbd in the course of the project		check the safety controller's ability to reduce the influence of unwanted torque steps
CORNERING STABILITY UNDER DECELERATION.	tbd in the course of the project		check the safety controller's ability to reduce the influence of unwanted torque steps

5.2.4 Manoeuvrability

For manoeuvrability, proven manoeuvres an thresholds are taken from Australian PBS. Namely these are Tail Swing and Low speed swept path. Details on these KPIs are outlined in Section 6.

5.2.5 Requirements to a vehicle dynamics controller

To avoid critical driving situations a controller will be developed that can set appropriate limits to the torques and torque gradients of the drive axles for both recuperation and acceleration. During the development of the controller which will be an iterative process both control algorithm and manoeuvres, criteria and thresholds will be finalized. In summary, the requirements for the vehicle dynamics controller are:

- The controller shall ensure that the AEMPT vehicle fulfils the criteria named above
- The controller shall work based upon a defined list of input signals that enable it to interpret vehicle configuration and driving situation correctly. This list is currently being developed and comprises values

such as vehicle unit weights, geometric and kinematic parameters, vehicle speed, steering wheel angle, engine and retarder torque, current gear, lateral and longitudinal accelerations and yaw rates.

- The controller shall be able to operate different vehicle configurations, in line with the general aim of AEROFLEX to allow for flexible combination of vehicle units.
- The controller shall take into account an combustion engine and multiple electric drives
- The controller should limit the torques of the electric axles not more than absolutely necessary for driving stability.
- The controller shall allow high torques at low speeds in order to not restrict startability.

5.3 Driveability

Driveability refers to the ability of the vehicle to follow typical infrastructure and traffic situations. To set up according requirements for AEMPT vehicles, the findings of FALCON (2) serve as a base, which in turn refer to the Australian PBS.

5.3.1 Traction Demand

The startability criteria describes the ability to start the vehicle at a slope from rest. In Australian PBS a minimum slope of 12% for level 2 is required. The performance of a vehicle in this criteria results from

- Total torque that can be applied to the driven axles
- Percentage of load on driven axles compared to overall vehicle load.

As regards load distribution, directive 96/53/EC requires for cross border transport that the weight on the driving axles must not be less than 25% of the total laden weight of the combination. For a 60ton, 25m vehicle having 8 axles in total and one driven axle this results in a necessary weight of 15 tons on the driven axle which conflicts with the allowed axle weight, also defined in Directive 96/53/EC. Accordingly, to comply with the 25% rule, a conventionally driven 25m EMS vehicle should include a 6x4 pulling unit which of course raises vehicle costs and fuel consumption. A 32m A-double combination does often not even reach 25% weight on driven axles with a 6x4 tractor, which results in wheel spin events (10). By using a single e-axle in a 25,25m EMS vehicle, e.g. in an e-dolly or e-trailer the 25% target can easily be reached in combination with one conventionally driven axle. For a 32m A-double configuration the 25%- rule is fulfilled by combining a conventional 4x2 tractor with two electrically driven axles in the other vehicle units or single e-axle together with a 6x4 pulling unit.

This finding highlights that a logistic company could continue running their operations using 4x2 tractors and semitrailers. By using AEMPT-vehicles, the company can flexibly use a conventional tractor-semitrailer combination or a A-double EMS2 vehicle depending on the use case and in any case complying with the 25% rule. As this is a clear advantage in terms of flexibility, the assumption is made that for all AEMPT vehicles there is only a single conventionally driven axle.

For the AEMPT vehicles the 25% rule is taken as a requirement. Together with the applicable friction coefficient of 0.8 (Australian PBS) the necessary friction potential to reach the threshold 12% is guaranteed.

To reach level 2 (12%), assuming a tire radius of 0,5m, a total torque of 600Nm/ton GCW is necessary to overcome gravity force. For a 25,25m vehicle having a GCW of 60tons, this results in an overall wheel torque requirements of 36000Nm. As explained above, the 25% rule requires at least one electrically driven axle for an 25,25m AEMPT vehicle. Assuming a uniform torque distribution this results in 18000Nm which are required at the wheels of the electrically driven axle. Of course this torque may be split among multiple electrically driven axles which would further increase traction potential for low mu. For a 74ton EMS2 configuration two electrically driven axles in addition to the combustion engine have been found to be necessary in order to fulfil the 25% rule. The overall torque requirement of 600Nm/ton GCW accordingly results in 45000 Nm, uniformly split among the three driven axles. For each electrically driven axle this results in a torque requirement of 15000Nm.

5.3.2 Power demand

As a first criteria for power demand, the Gradeability B criteria of Australian PBS will be used. For level 2 and level 3, this criteria requires to hold a speed of 70km/h on a 1% slope. Simulations which have been done at MAN show that a power of 5,25 kW/ton is necessary to fulfil this criteria. As there is no time constraint for this criteria, this power should be available independently of a battery capacity. Therefore, the combustion engine alone should be capable of supplying this power. As an Example, a 12l 500hp combustion engine would suit a combination up to 70tons.

As a second criteria for power demand, Acceleration Capability of Australian PBS is used. This criterion describes the capability of accelerating the vehicle from rest. It is relevant for e.g. to pass crossings or entering highways. According to Australian PBS a 100m track distance has to be completed in 23s for Level 2. In order to evaluate, how this criteria applies on AEMPT vehicles, longitudinal simulations have been done. To reach the level 2 threshold, a power demand of 4,5kW/ton has been found. As this value is substantially lower than the required power for gradeability, it can be neglected.

As explained in section 3, an AEMPT vehicle requires electric power of at least 4kW/ton GCW for reaching efficiency goals. In all situations which require high drive power, the electric drives will extend the performance of the vehicles considerably. Of course until the battery is depleted.

5.4 Requirements to the AEMPT and KPIs

Index	Dependent from Index	Category	Requirements	Comment/KPIs
VD - 1		Vehicle Dynamics	The dynamic behaviour of an AEMPT vehicle fulfil at least the requirements for conventionally driven EMS vehicles	
VD - 2	VD - 1	Vehicle Dynamics	Tracking Ability On A Straight Path shall be within 3m	KPI: Tracking Ability On A Straight Path
VD - 3	VD - 1	Vehicle Dynamics	Static Rollover Threshold shall be larger than 0,35g	KPI: Static Rollover Threshold
VD - 4	VD - 1	Vehicle Dynamics	Rearward Amplification shall be not greater than 5.7 times the static rollover threshold of the rearmost unit	KPI: Rearward Amplification
VD - 5	VD - 1	Vehicle Dynamics	High-Speed Transient Offtracking shall be smaller than 0,8m	KPI: High-Speed Transient Offtracking
VD - 6	VD - 1	Vehicle Dynamics	The Yaw Damping Coefficient shall be not less than 0.15	KPI: Yaw Damping Coefficient
VD - 7	VD - 1	Vehicle Dynamics	The vehicle shall show a minimum deceleration from 60km/h of 0.35g within a lane width of 3.0 m	KPI: Directional Stability Under Braking
VD – 8	VD - 1	Vehicle Dynamics	The steering angle gradient shall always be in the range of <tbd>	KPI: Steering Angle Gradient
VD – 9		Vehicle Dynamics	When accelerating in a curve, the vehicle shall show a stable behaviour	KPI: Cornering Stability Under Acceleration.
VD – 10		Vehicle Dynamics	When decelerating in a curve, the vehicle shall show a stable behaviour	KPI: Cornering Stability Under Deceleration.
VD – 11		Vehicle Dynamics	A vehicle dynamics controller shall limit torque requests to the electric axles in order to guarantee a stable vehicle behaviour	
VD - 12	VD- 11	Vehicle Dynamics	The vehicle dynamics controller should limit the torques of the electric axles not more than necessary for driving stability	KPI: Fuel consumption in l/100km Restrictions on electric torques have negative effects on fuel efficiency.
VD - 13	VD- 11		The vehicle dynamics controller shall work based upon a defined list of input	

			signals that enable it to interpret the vehicle configuration and driving situation correctly	
VD – 14		Vehicle Dynamics	The traction monitoring should not be done in the vehicle controller but locally in the traction modules	
VD - 15		Vehicle Dynamics	Anti-Lock control during recuperation should not be done in the controller but locally in the traction modules	
VD - 16	VD - 12	Vehicle Dynamics	High traction at low speeds should be possible.	KPI: Acceleration Capability, Startability
VD - 17	VD - 1	Vehicle Dynamics	AEMPT vehicles shall be startable at a 12% slope	KPI: Startability
VD -18	VD - 1	Vehicle Dynamics	At least 25% of the vehicle weight shall be carried by driven axles	KPI: Acceleration Capability, Startability
VD - 19	VD - 17	Vehicle Dynamics	AEMPT vehicles up to 25,25m and up to 60ton GCW shall at least have one electrically driven axle, in addition to a conventionally driven axle.	
VD -20	VD - 17	Vehicle Dynamics	AEMPT vehicles longer than 25,25m and up to 74ton GCW shall at least have two electrically driven axle, in addition to a conventionally driven axle.	
VD -21	VD - 17	Vehicle Dynamics	For AEMPT vehicles up to 25,25m and up to 60ton GCW the wheel torque of electrically driven axles shall exceed 18000Nm at v=0km/h	
VD - 22	VD - 17	Vehicle Dynamics	For AEMPT vehicles longer than 25,25m and up to 74ton GCW the wheel torque of electrically driven axles shall exceed 30000Nm at v=0km/h, wherein for each electrically driven axle a maximum of 15000Nm is added to this value	A configuration of two axles having a torque potential of 5000Nm and 25000Nm respectively is not valid.
VD -23	VD - 1	Vehicle Dynamics	AEMPT vehicles shall be able to drive a 1% Slope continuously at 70km/h	KPI: Gradeability
VD -24	VD - 23		AEMPT vehicles up to 25,25m and up to 60ton GCW shall have a combustion engine power of at least 315kW	KPI: Gradeability, Acceleration Capability
VD -25	VD - 23		AEMPT vehicles longer than 25,25m and up to 74ton GCW shall have a combustion engine power of at least 388kW	KPI: Gradeability, Acceleration Capability

6 Definition of KPIs

In this section, KPIs are defined which will be used to assess the performance of the technical solution of AEROFLEX WP2.

6.1 Efficiency

6.1.1 Fuel Consumption in l/100km

Name	WP2 - Fuel Consumption in l/100km
Description	Average vehicles fuel consumption in litres fuel (diesel) consumed per driven kilometre over a particular trip. It also contains relative fuel consumption using the same absolute values compared to a specific reference vehicle configuration.
Unit	[l/100 km], [% - fuel saving]
Target value	Relative: 12% compared to conventional reference vehicles of the same type.
Equation	Absolute: $\frac{Fuel\ consumption\ [litre\ ]}{distance\ [100km]}$ Relative: $\frac{\left(Fuel\ consumption\ ref.vehicle\ \left[\frac{l}{km}\right] - Fuel\ consumption\ vehicle\ with\ feature\ \left[\frac{l}{km}\right]\right)}{Fuel\ consumption\ ref.vehicle\ \left[\frac{l}{km}\right]} \cdot 100\%$
Comparison	The AEROFLEX AEMPT features are compared with a similar conventional vehicle: 1. AEMPT tractor-E-Semitrailer <-> conventional tractor semitrailer 2. AEMPT tractor-E-Semitrailer <-> tractor-Transformers-trailer (Advanced Reference) 3. AEMPT 6x2 truck-dolly-semitrailer (EMS1) <-> conventional 6x2 truck-dolly-semitrailer 4. AEMPT 4x2 tractor-semitrailer-dolly-semitrailer (EMS2) <-> conventional 4x2 tractor-semitrailer-dolly-semitrailer Cases 1 and 2 are assessed virtually whereas 3 and 4 are part of test track and public road tests. Results from measurements on two test use-cases: • Proving ground cycle • Real-world test cycle Results from simulations: • Similar cycles as measurements • Additional long haul cycles Remark: • If no cyclic behaviour can be achieved during tests, the fuel consumption needs to be corrected for the difference in State-of-Charge of the batteries before and after the test.

6.1.2 Fuel Efficiency in l/ton-km

Name	WP2 –Fuel Efficiency in l/ton-km
Description	Vehicles fuel efficency in litres fuel (diesel) consumed per driven kilometre and ton payload over a particular trip. It also contains relative fuel efficency using the same absolute values compared to a specific reference vehicle configuration.
Unit	[l/ton- km], [% - fuel efficiency improvements]
Target value	Relative: 12% compared to conventional reference vehicles of the same type.

Equation	Absolute: $\frac{Fuel\ consumption\ [litre]}{distance\ [km] * payload\ [tonnes]}$ Relative: $\frac{\left(Fuel\ consumption\ ref.vehicle\ \left[\frac{l}{km}\right] - Fuel\ consumption\ vehicle\ with\ feature\ \left[\frac{l}{km}\right]\right)}{Fuel\ consumption\ ref.vehicle\ \left[\frac{l}{km}\right]} \cdot 100\%$
Comparison	The AEROFLEX AEMPT features are compared with a similar conventional vehicle: 1. AEMPT tractor-E-Semitrailer <-> conventional tractor semitrailer 2. AEMPT tractor-E-Semitrailer <-> tractor-Transformers-trailer (Advanced Reference) 3. AEMPT 6x2 truck-dolly-semitrailer (EMS1) <-> conventional 6x2 truck-dolly-semitrailer 4. AEMPT 4x2 tractor-semitrailer-dolly-semitrailer (EMS2) <-> conventional 4x2 tractor-semitrailer-dolly-semitrailer Cases 1 and 2 are assessed virtually whereas 3 and 4 are part of test track and public road tests. Results from measurements on two test use-cases: • Proving ground cycle • Real-world test cycle Results from simulations: • Similar cycles as measurements • Additional long-haul cycles Remark: • If no cyclic behaviour can be achieved during tests, the fuel consumption needs to be corrected for the difference in State-of-Charge before and after the test.

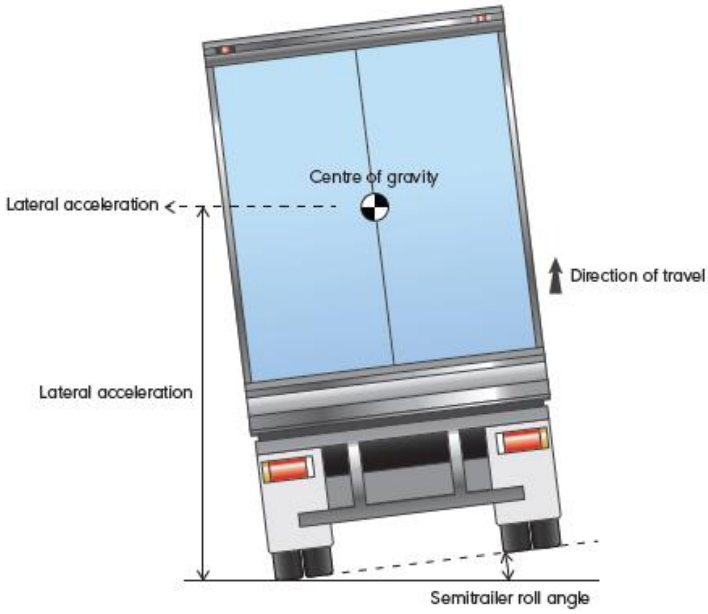
6.1.3 Average Speed

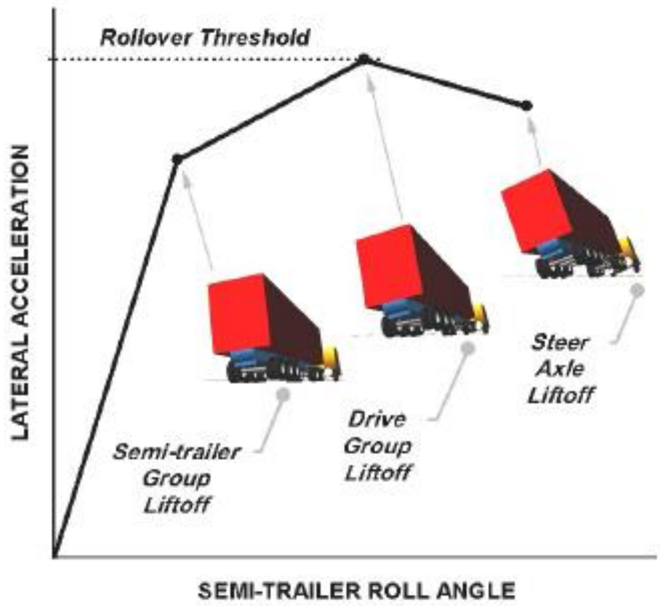
Name	WP2 –Average Speed
Description	Average speed at the cycle which is used for the assessment of fuel consumption. For validly comparing fuel consumption of two vehicle configurations the average speed should be approximately the same. AEMPT vehicles shall not show higher average speeds than conventional vehicles as this is disadvantageous for fuel consumption.
Unit	[km/h]
Target value	Not applicable
Equation	$\frac{distance\ of\ cycle\ [km]}{time\ to\ complete\ cycle\ [h]}$
Comparison/Test Definition	To be calculated for all measurements and simulations used for assessing fuel consumption.

6.2 Lateral Stability

6.2.1 Static Rollover Threshold

Name	WP2 – Static Rollover Threshold
Description	Static Rollover Threshold (SRT) is the level of lateral force a vehicle can sustain without rolling over while travelling along a curved path. High values of SRT imply better resistance to rollover. Rollover occurs when the lateral (or sideways) acceleration is sufficient to exceed the vehicle's rollover stability threshold.

	The primary purpose of this standard is to manage safety risk by limiting the rollover tendency of a vehicle combination during turns. 
Unit	[g], [m/s^2]
Target value	<u>Absolute:</u> SRT ≥ 0.35g (≈ 3.5 m/s^2) The rollover threshold of the vehicle, or vehicle unit with the lowest rollover stability, must be measured and reported as the achieved performance value, expressed as a fraction of the acceleration due to gravity in units of 'g', rounded down to the nearest 0.01g. For single unit vehicles, such as rigid trucks, buses and coaches, the rollover threshold is the lateral acceleration of the sprung mass centre of gravity measured at the point of rollover instability. For combination and multi-combination vehicles, the rollover threshold is the resultant lateral acceleration of any unit, measured at the point of rollover instability. Rollover instability is achieved when the lateral acceleration, or resultant lateral acceleration, starts to decrease with increasing roll angle, as illustrated in Figure below for a prime mover and semi-trailer vehicle or roll-coupled set.

	 In general for heavy vehicles, the point of roll instability is also achieved when, or immediately after, the vertical load on all tyres along one side of the vehicle, excluding the tyres on the lightly loaded side of a steer axle(s) with soft springs, have reduced to zero. Vehicles that reach or exceed the tyre/road friction limits before rollover occurs, and achieve a steady state lateral acceleration that is not less than the required performance level are deemed to have acceptable rollover stability.
Equation	Absolute: N/A
Comparison/Test Definition	The vehicle being assessed must be tested at the maximum laden mass and in both turn directions at the least favourable load conditions corresponding to maximal operational loading. Each tyre on the vehicle must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tyre. Each tyre must be inflated to the pressure as specified by the vehicle and/or tyre manufacturer. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. One of the following two test procedures must be used to measure static rollover threshold: (i) Constant radius quasi-steady turn – The vehicle being assessed must be driven along the specified path at an initial speed that is at least 10 km/h slower than the speed at which the rollover instability will occur. The path of the specified turn that the driver will use to guide the vehicle must be circular and of radius not less than 100 metres. In the turn the driver must steer the vehicle along the specified path. The vehicle must be steered such that the vertical projection in the ground plane of a point at the centre of the forward-most steer axle follows the specified path. Using the above point as a reference, the driver must steer the vehicle along the specified path and maintain a lateral distance error between the reference point and the specified path not greater than 1.5 metres. From the initial speed, which must be maintained for at least 15 seconds on the specified path, the driver must increase the speed of the vehicle to the point of rollover instability at:

<table>
<tr><td></td><td>(a) an average rate, measured over any 5-second period, not greater than 0.5 km/h per second; or

(b) in increments of 2 km/h per lap.

This procedure is particularly relevant to long multi-combination vehicles that take much longer to reach steady turn conditions than short vehicles.

For the safety reasons the test method can be performed by means computer-based simulation instead of field testing.</td></tr>
</table>

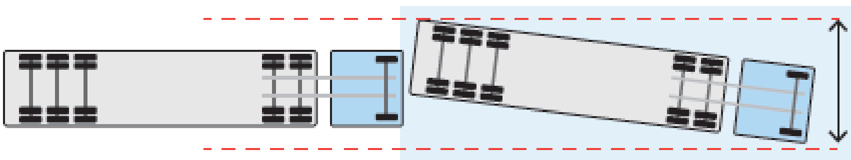
6.2.2 Directional Stability Under Braking

<table>
<tr><td>Name</td><td>WP2 – Directional Stability Under Braking</td></tr>
<tr><td>Description</td><td>The purpose of the directional stability assessment is to manage the safety risk of vehicle instability when braking in a turn or on pavement cross slopes.

A vehicle must not exhibit gross wheel lock-up behaviour (ABS is activated) in any loading condition and must remain in a straight lane of the specified width for the corresponding level of operation when it is braked from 60 km/h.

Furthermore maximum brake pedal actuation is considered.</td></tr>
<tr><td>Unit</td><td>[g], [m/s^2]</td></tr>
<tr><td>Target value</td><td><u>Absolute:</u>
Average deceleration from 60 km/h

<table>
<tr><th>Level</th><th>Required minimal average deceleration from 60km/h</th><th>Allowed width of the lane during the barking [m]</th></tr>
<tr><td>1</td><td>0.4g</td><td>2.9</td></tr>
<tr><td>2</td><td>0.35g</td><td>3</td></tr>
<tr><td>3</td><td>0.3g</td><td>3.1</td></tr>
<tr><td>4</td><td>0.25g</td><td>3.3</td></tr>
</table>


</td></tr>
<tr><td>Equation</td><td><u>Absolute:</u>

Average deceleration = ½ (initial speed in m/s)^2 / (g x stopping distance in m)

where g = 9.81 m/s2 and stopping distance measured in accuracy of 0.1m.</td></tr>
<tr><td>Comparison/Test Definition</td><td>The vehicle being assessed should be tested in the laden condition. If the vehicle complies in the unladen condition, it is deemed to comply in the laden condition. Each tyre on the vehicle</td></tr>
</table>

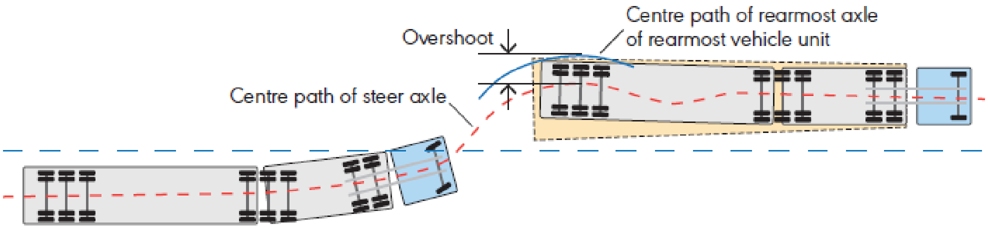
	must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tyre. Each tyre must be inflated to the pressure as specified by the vehicle and/or tyre manufacturer. The tread depth of each tyre must not decrease by more than 2 mm during field testing. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. The test (initial) speed should be in the range 59 – 65 km/h. The point where deceleration starts and the point where the vehicle stops should be marked on the test roadway.

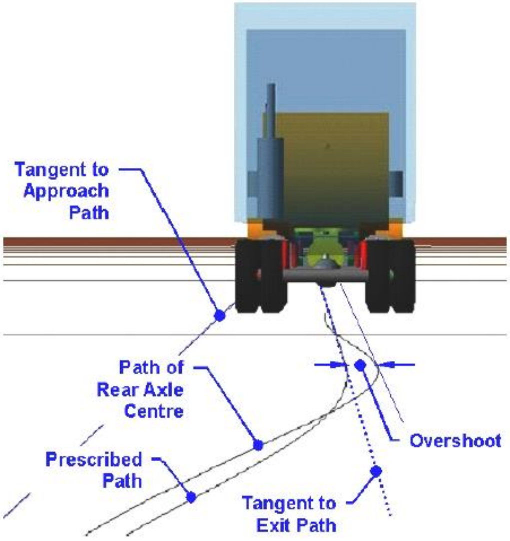
6.2.3 Rearward Amplification

Name	WP2 – Rearward Amplification
Description	Rearward Amplification (RA) is the degree to which the trailing unit/s amplify the lateral (sideways) movement of the hauling unit. It generally relates to heavy vehicles with more than one articulation point. These vehicles exhibit a tendency for the trailing unit/s to experience higher levels of lateral acceleration (sway) than the hauling unit. The amount of sway exhibited by the trailing units is a serious safety concern in rapid path-change manoeuvres and can lead to rear-trailer rollover. The primary purpose of this assessment is to manage safety risk by limiting the lateral directional response of multi-articulated vehicle combinations in avoidance manoeuvres performed at highway speeds without braking.
Unit	[-]
Target value	<u>Absolute:</u> RA ≤ 5.7*Static rollover threshold
Equation	<u>Absolute:</u> $$RA = \frac{\lvert AY \rvert_{max} \; of \; following \; vehicle \; unit}{\lvert AY \rvert_{max} \; of \; first \; vehicle \; unit}$$ The following is ascribed to the numerator and the denominator terms, respectively: $\lvert AY \rvert_{max}$ *of following vehicle unit* = maximum absolute value of the lateral acceleration of the centre of mass of the sprung mass of the last vehicle unit (m/s^2) $\lvert AY \rvert_{max}$ *of first vehicle unit* = maximum absolute value of the lateral acceleration of the centre of the front axle (m/s^2)
Comparison/Test Definition	The vehicle must execute a single lane change manoeuvre in accordance with the “Single Lane-Change”, “Single Sine-Wave Lateral Acceleration Input”, specified in ISO 14791:2000(E) (International Standards Organisation, 2000)17. The basic course layout must be used. The manoeuvre must have a maximum lateral acceleration of not less than 0.15g and a steer frequency equal to 0.40 Hz. The test must be conducted at 88 km/h. The driver must steer the vehicle along the specified path and maintain a lateral distance error between the reference point – taken to be the vertical projection in the ground plane of the centre of the forward most steer axle – and the specified path that is either: • not greater than 30 mm; or,

	• as specified in ISO 14791 such that the lateral acceleration and frequency of the input is not less than the value for the manoeuvre specified in the paragraph above.

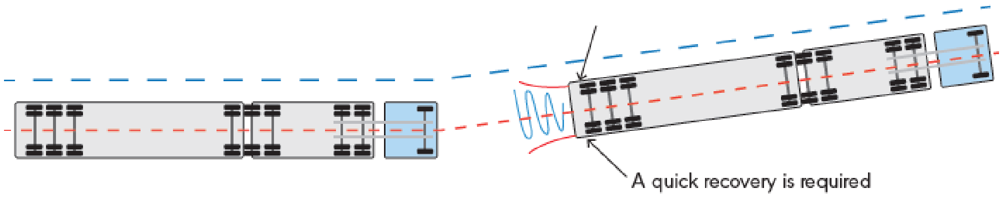
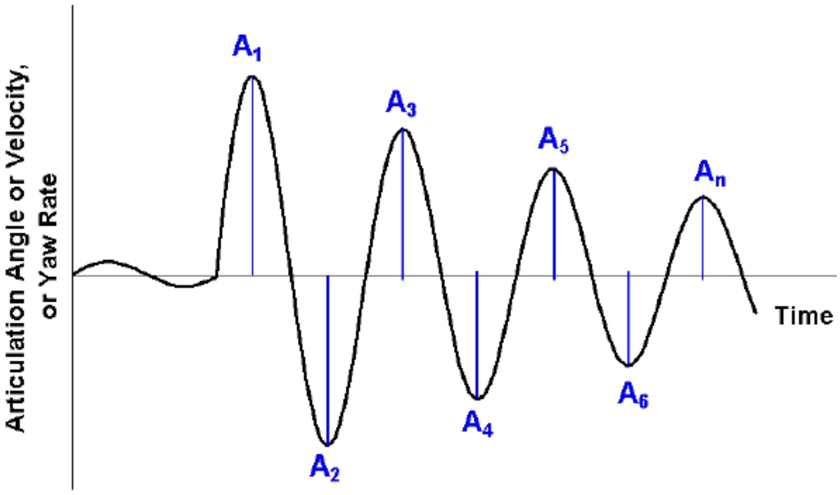
6.2.4 High Speed Transient Offtracking

Name	WP2 – High Speed Transient Offtracking
Description	High Speed Transient Offtracking (HSTO) is the distance that the last axle on the rearmost trailer tracks outside the path of the steer axle in a sudden evasive manoeuvre. In a sudden evasive manoeuvre, the sideways movement of the rear end of a vehicle may extend beyond or 'overshoot' that of the hauling unit. The amount of overshoot (referred to as HSTO), can be viewed as an indication of the severity of intrusion into an adjacent or opposing lane, striking a kerb or dropping off the road seal (thus precipitating rollover), or collision with a road-side objects. The primary purpose of this standard is to manage safety risk by limiting the sway of the rearmost trailers of multi-articulated PBS vehicles in avoidance manoeuvres performed at highway speeds without braking. 
Unit	[m]
Target value	<u>Absolute:</u> L1≤ 0.6 m; L2≤ 0.8 m; L3 ≤ 1 m, L4≤ 1.2 m The maximum lateral distance between the path trajectory of the specified point on the vehicle being assessed, measured in the ground plane and perpendicular to the exit tangent of the single lane change, single sine-wave lateral acceleration input, test course must be measured and reported as the achieved performance value, expressed in units of metres and rounded up to the nearest 0.1 metre. The specified point on the vehicle is the vertical projection in the ground plane of a point at the centre of the rearmost axle of the rearmost vehicle unit, as illustrated below.

	
Equation	Absolute: N/A
Comparison/Test Definition	The vehicle must execute a single lane change manoeuvre in accordance with the “Single Lane-Change”, “Single Sine-Wave Lateral Acceleration Input”, specified in ISO 14791:2000(E) (International Standards Organisation, 2000)17. The basic course layout must be used. The manoeuvre must have a maximum lateral acceleration of not less than 0.15g and a steer frequency equal to 0.40 Hz. The test must be conducted at 88 km/h variation of -3 and +5 km/h . The driver must steer the vehicle along the specified path and maintain a lateral distance error between the reference point – taken to be the vertical projection in the ground plane of the centre of the forward most steer axle – and the specified path that is either: • not greater than 30 mm; or, • as specified in ISO 14791 such that the lateral acceleration and frequency of the input is not less than the value for the manoeuvre specified in the paragraph above.

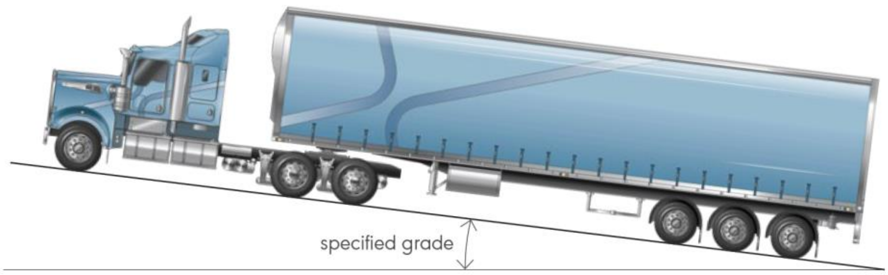
6.2.5 Yaw Damping

Name	WP2 – Yaw Damping
Description	The Yaw Damping Coefficient (D) performance measure quantifies how quickly ‘sway’, or yaw oscillations take to settle after application of a short duration steer input at the hauling unit. An important consideration in the stability and handling of heavy vehicles is how quickly swing or sway oscillations take to ‘settle down’ or decay after a severe manoeuvre has been performed. Vehicles that take a long time to settle represent a higher safety risk to other road users and to the driver. The primary purpose of this standard is to manage safety risk by requiring acceptable attenuation of any sway oscillations of articulated vehicle combinations.

	
Unit	[-]
Target value	<u>Absolute:</u> D ≥ 0.15 The damping ratio calculated from the specified motion variable in the specified test must be measured and reported as the achieved performance value, expressed as a dimensionless quantity and rounded down to the nearest 0.01. The specified motion variable is the articulation angle, or articulation angular velocity, between adjacent units, or the yaw rate of a unit, which gives the lowest damping of the vehicle combination.
Equation	<u>Absolute:</u> From the time history of the motion variable, all amplitudes starting with the first largest amplitude, A_1, after application of the specified steer input must be determined, as illustrated in Figure below.  The mean value of the amplitude ratios, Ā, must be calculated separately for each articulation joint, or unit, using the following equation:

	$\overline{A} = \frac{1}{n-2}\left(\frac{A_1}{A_3} + \frac{A_2}{A_4} + \frac{A_3}{A_5} + \ldots + \frac{A_{n-2}}{A_n}\right)$ Amplitude A_n must be at least 5% of A_1 and the calculation of $\bar{A}$ must be based upon at least 6 amplitudes. The damping ratio, D, is calculated according to the following formula: $D = \frac{\ln(\overline{A})}{\sqrt{(2\pi)^2 + [\ln(\overline{A})]^2}}$, If the 5% limit referred to above is reached before the 6^{th} amplitude, then the following formulae may be used in place of equations (C14a) and (C14b), respectively: $\overline{A} = \frac{1}{n-1}\left(\frac{A_1}{A_2} + \frac{A_2}{A_3} + \frac{A_3}{A_4} + \ldots + \frac{A_{n-1}}{A_n}\right)$ $D = \frac{\ln(\overline{A})}{\sqrt{(\pi)^2 + [\ln(\overline{A})]^2}}$,

6.3 Driveability

Name	WP2 – Vehicle combination Gradeability (A, B)
Description	Gradeability is the ability of the vehicle to maintain forward motion on a specified upgrade. The primary purpose of this standard is to manage safety risks associated with travel on grades by ensuring a PBS vehicle has the capability to maintain acceptable speeds on upgrades. Part A is the ability of a vehicle to maintain forward motion on a specified upgrade. Part B is the ability of a vehicle to maintain minimum speed on a specified upgrade. 
Unit	Achieved upgrade gradient slope [%[1]] (Part A), Minimal forward speed [km/h] (Part B)
Target value	<u>Absolute:</u> Gradeability Part A (Maintain motion) L1≥ 20%; L2≥ 15%; L3≥ 12%, L4≥ 8% Gradeability Part B (Maintain speed) L1≥ 80 km/h; L2≥ 70 km/h, L3≥ 70 km/h, L4≥ 60 km/h Part A - The maximum upgrade on which steady forward motion is maintained must be measured and reported as the achieved performance value, in units of percentage grade rounded down to the nearest whole number.

[1] Percentage grade is defined to mean 100 times the change-in-height divided by the (horizontal) distance over which the height change occurs. A grade of 100% corresponds to a grade line of 1:1 or 45º incline, a grade of 10% would be 1:10, or a 5.7º incline.

	Part B - When operating at operational laden mass, a vehicle must be able to maintain a specified minimum speed on a pavement section having an upgrade of not less than 1%. An initial change in speed associated with the transition from the approach to the upgrade is acceptable, provided the specified minimum speed is maintained on the upgrade.
Comparison /Test definition	Vehicles will be compared in absolute manner using defined performance measures. Comparison however should not be interpreted in a sense one vehicle is better than another. It implies the vehicle should not be operated on infrastructure segments which exceeds the performance of the vehicle. The vehicle being assessed must be loaded to its operational mass. Each tyre on the vehicle must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tyre. Each tyre must be inflated to the pressure as specified by the vehicle and/or tyre manufacturer. The full length of the vehicle while being assessed must be on an upgrade appropriate to the road classification level. Additionally, the upgrade must be of sufficient length to allow steady forward motion to be established. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. Part A With the vehicle being assessed in forward motion on a slope having an upgrade not less than the specified grade, it must maintain steady forward motion. Steady forward motion is achieved when the vehicle's forward speed on the upgrade is either constant or increasing for a distance of at least 5 metres. Part B With the vehicle being assessed in forward motion on a slope having an upgrade of not less than 1%, steady forward motion must be maintained at a speed at least equal to the specified minimum speed. Steady forward motion is when the forward speed of the vehicle on the upgrade is either constant or increasing for a period of at least 5 seconds.

6.3.1 Startability

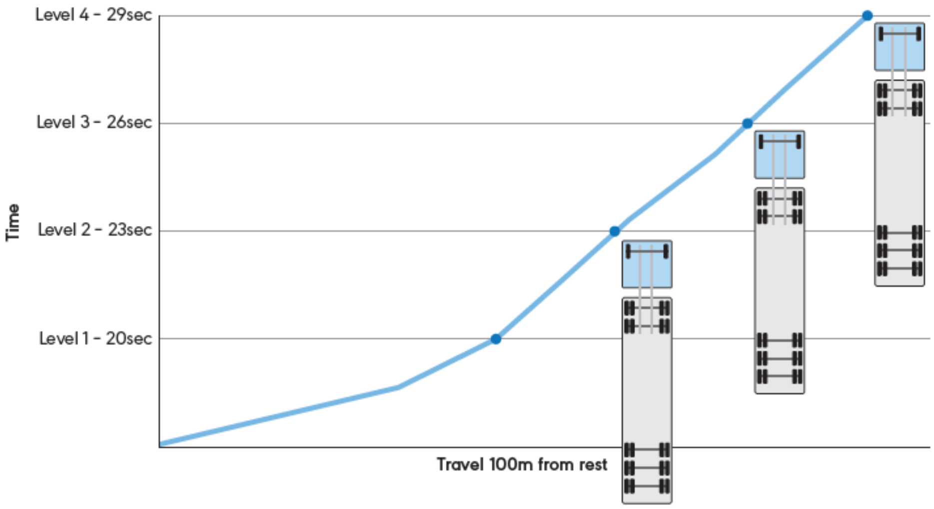
Name	WP2 – Startability
Description	Startability is the ability to commence forward motion on specified upgrade from stand-still conditions. The primary purpose of this standard is to manage safety risks associated with starting on grades by ensuring a vehicle combination has adequate starting capability on grades. This means that a vehicle combination has been assessed as capable of starting on the steepest grade it has to negotiate on the nominated route when operating at its maximum allowed gross mass. This is to ensure it does not become a safety risk or inconvenience to other road users. 

Unit	Achieved upgrade gradient slope [%[2]]
Target value	Absolute: L1≥ 15%; L2≥ 12%; L3≥ 10%, L4≥ 5% The maximum upgrade on which forward motion is commenced and maintained must be measured and reported as the achieved performance value, in units of percentage grade, rounded down to the nearest whole number.
Equation	Absolute: N/A
Comparison /Test Definition	The vehicle being assessed must be loaded to its maximum laden mass. Each tyre on the vehicle must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tyre. Each tyre must be inflated to a pressure within the range as specified by the vehicle and/or tyre manufacturer. The full length of the vehicle being assessed must be on an upgrade appropriate to the road classification level. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. From a standing start on a slope having an upgrade not less than the specified grade, the vehicle being assessed must commence and maintain steady forward motion. Steady forward motion on the specified grade is achieved when the vehicle's speed is either constant or increasing for a distance of at least 5 metres.

6.3.2 Acceleration Capability

Name	WP2 – Acceleration Capability
Description	Acceleration Capability is the ability of the vehicle to either accelerate from rest or increase speed on a road with no grade. The primary purpose of this standard is to manage safety risk associated with travel through intersections and rail crossings by specifying minimum times for a vehicle participating in the Scheme to accelerate from rest, to increase speed, and travel specified distances.
Unit	[sec]
Target value	Absolute: The time taken to travel the distance of 100 metres must be reported as the achieved performance, to the nearest 0.1 second.

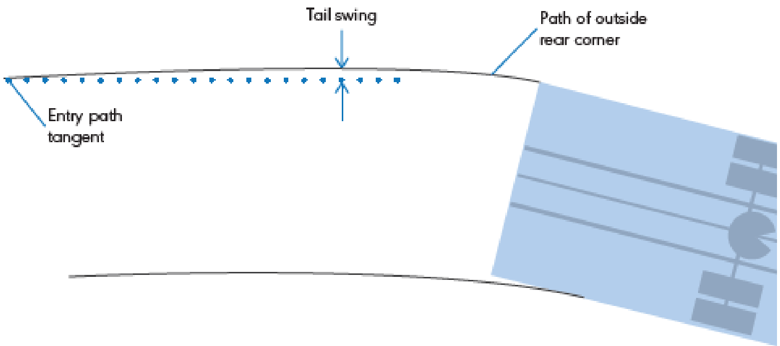
[2] Percentage grade is defined to mean 100 times the change-in-height divided by the (horizontal) distance over which the height change occurs. A grade of 100% corresponds to a grade line of 1:1 or 45º incline, a grade of 10% would be 1:10, or a 5.7º incline.

	
Equation	Absolute: N/A
Comparison/Test Definition	The vehicle being assessed must be loaded to its maximum laden mass. Each tyre on the vehicle must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tyre. Each tyre must be inflated to the pressure as specified by the vehicle and/or tyre manufacturer. The full length of the vehicle being assessed must be on a site with zero grade throughout the test. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. From a standing start the vehicle being assessed must accelerate, changing through the gears as required, over a distance of at least 100 metres. The point of commencement of acceleration should be taken as the moment forward motion starts.

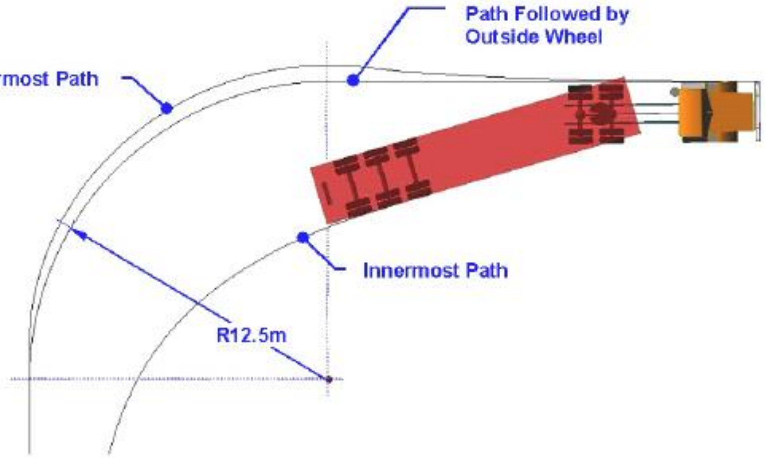
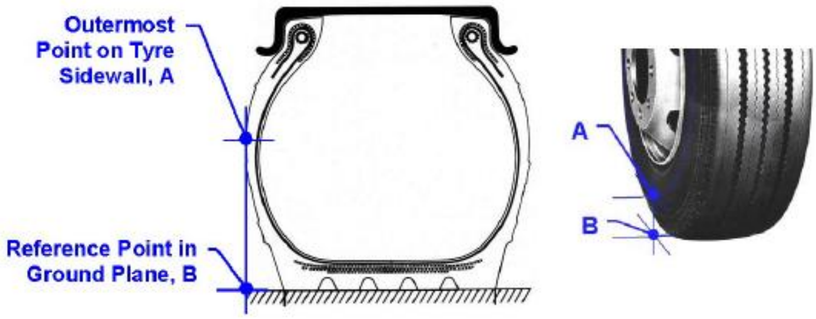
6.4 Manoeuvrability

6.4.1 Tail Swing

Name	WP2 – Tail Swing
Description	Tail Swing is the maximum outward lateral displacement of the outer rearmost point on a vehicle unit during the initial and final stages of a prescribed 90° low-speed turn. Tail Swing is typically of more concern in urban areas. Vehicles with significant rear overhang (e.g. route buses or semitrailers) and/or coupling rear overhangs will exhibit significant amounts of tail swing when negotiating tight manoeuvres (e.g. buses and coaches exiting kerbside pickup areas). The primary purpose of this standard is to manage safety risk by limiting the road space requirement of a vehicle combination when making a tight turn at low speed.
Unit	[m]
Target value	Absolute: L1≤0.3 m; L2≤ 0.35 m; L3 ≤0.35m, L4≤ 0.5 m

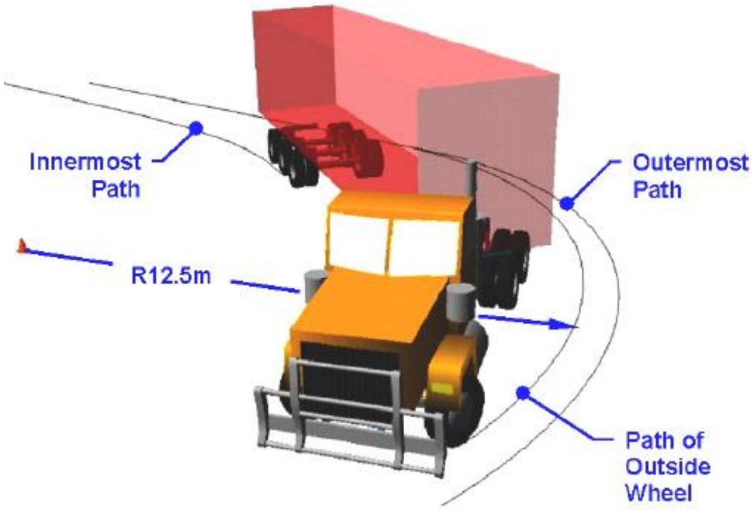
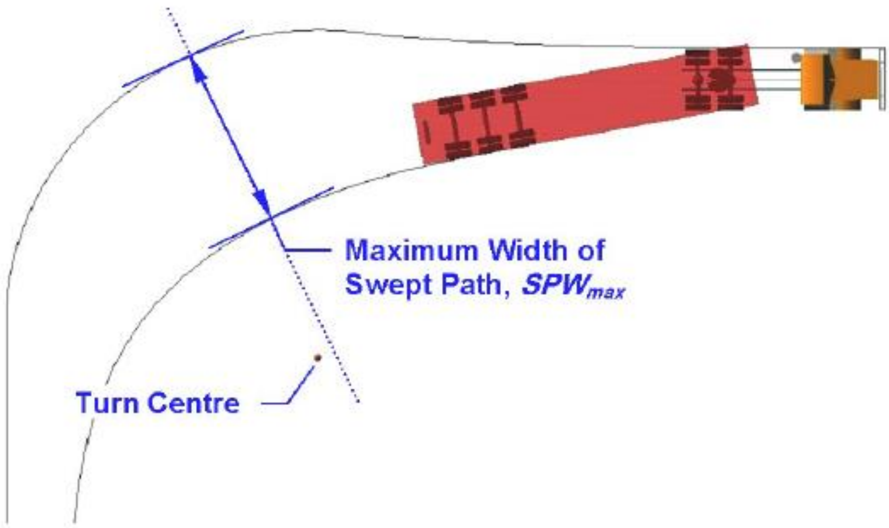
	The maximum tail swing during the initial and final stages of the prescribed turn, referred to as TS_{entry} and TS_{exit}, respectively, must be measured and reported as the achieved performance value, in units of metres rounded up to the nearest 0.01 metre. Tail swing must be determined from the path trajectory of the outermost path scribed in the ground plane by the vertical projection of the furthest rearward or outside point, or points, on the vehicle unit having the greatest tail swing. On the entry side of the turn, tail swing is the length of the longest line segment perpendicular to the low-speed turn entry tangent intersecting it and the path trajectory as shown below. 
Equation	Absolute: N/A
Comparison /Test Definition	The vehicle being assessed must be tested fully laden and unladen. When fully laden it must be loaded to its maximum allowed gross mass and the corresponding maximum allowed axle group loads must not be exceeded. For the purposes of measuring swept path, mirrors and signalling devices are ignored. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. The vehicle being assessed must be driven through the specified turn, unladen and laden, at a speed no greater than 5 km/h. The path of the specified turn that the driver will use to guide the vehicle must comprise straight tangent approaches to a 90° circular arc of 12.5 metre radius. The approaches to the turn must be of sufficient length to ensure: (i) the entire vehicle is straight at the point where the 90° turn is commenced; and (ii) at the conclusion of the turn the vehicle travels far enough into the straight exit segment to record the maximum width of the swept path. The driver must ensure the entire vehicle is straight at the commencement of the turn (within 0.1 metre of the entry approach tangent). In the turn the driver must steer the vehicle along the specified path. The vehicle must be steered such that the vertical projection in the ground plane of the outer most point on the outer tyre sidewall nearest to the ground[3], on the forward most outside steered-wheel, follows the specified path as illustrated below.

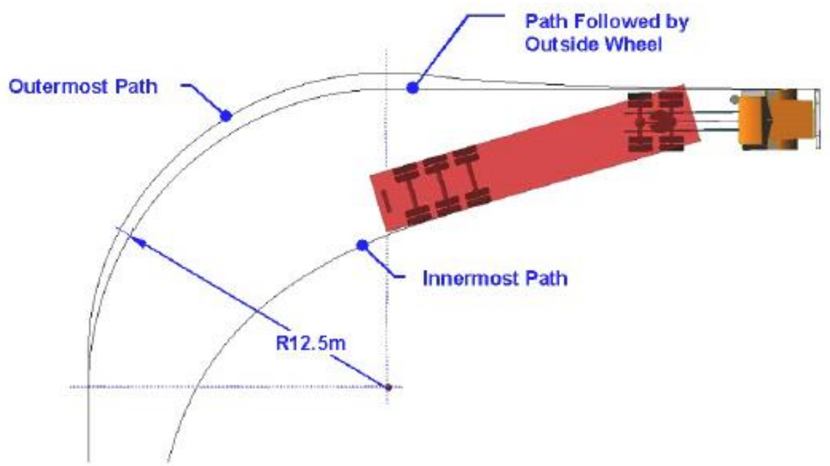
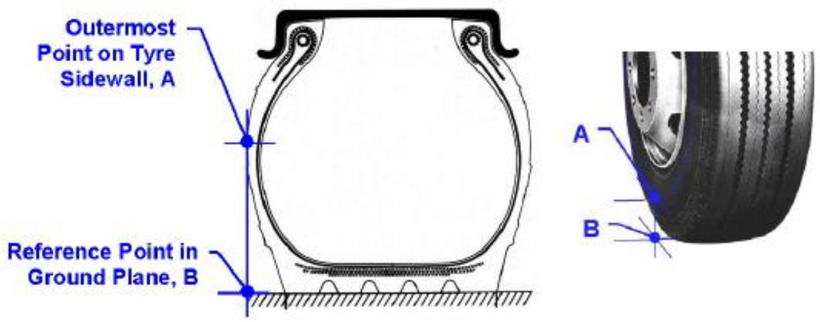
[3] This represents the outermost point on the tyre sidewall – including tyre bulge due to deflection – which is most likely to come into contact first with the kerb in a shallow angle strike.

	 Using the above point as a reference, the driver must steer the vehicle along the specified path and maintain a lateral distance error between the reference point B (see below) and the specified path not greater than 50 millimetres. 

6.4.2 Low Speed Swept Path

Name	WP2 – Low Speed Swept Path
Description	Low speed swept path is the maximum width of road space required for a vehicle to complete a 90° low-speed turn. When a long vehicle makes a low-speed turn at an intersection, the rear of the vehicle will follow a path that is inside the path taken by the front of the vehicle. Poor manoeuvrability performance may cause the vehicle to encroach into adjacent or opposing lanes, collide with parked or stopped vehicles, damage roadside furniture or endanger pedestrians, or its rear wheels may climb the kerb or fall off the edge of the pavement. The primary purpose of this standard is to manage safety risk associated with turns at intersections by limiting the road space required by vehicle combinations making low-speed turns.
Unit	[m]
Target value	Absolute: L1≤ 7.4 m; L2≤ 8.7 m; L3 ≤ 10.6 m, L4≤ 13.7 m The maximum width of the swept path must be measured and reported as the achieved performance value, in units of metres rounded up to the nearest 0.1 metre. The maximum width of the swept path is the maximum distance, SPW_{max}, between the outer and inner path trajectories of the swept path envelope of the vehicle being assessed in the specified low-speed turn, shown in Figures below.

	  The maximum distance, SPW_{max}, is the straight-line segment intersecting both trajectories perpendicularly to their respective tangents at the intersection points. The swept path must be determined from the path trajectories of: 1) the outermost path scribed in the ground plane by the vertical projection of the furthest forward or outside point, or points, on the vehicle on the outside of the turn; and 2) the innermost path scribed in the ground plane by the vertical projection of the point, or points, on the vehicle on the inside of the turn.
Equation	Absolute: N/A
Comparison/Test Definition	The vehicle being assessed must be tested fully laden and unladen. When fully laden it must be loaded to its maximum allowed gross mass and the corresponding maximum allowed axle group loads must not be exceeded. For the purposes of measuring swept path, mirrors and signalling devices are ignored.

	The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{max}, at the tyre/road contact surface of not more than 0.80. The vehicle being assessed must be driven through the specified turn, unladen and laden, at a speed no greater than 5 km/h. The path of the specified turn that the driver will use to guide the vehicle must comprise straight tangent approaches to a 90° circular arc of 12.5 metre radius. The approaches to the turn must be of sufficient length to ensure: (i) the entire vehicle is straight at the point where the 90° turn is commenced; and (ii) at the conclusion of the turn the vehicle travels far enough into the straight exit segment to record the maximum width of the swept path. The driver must ensure the entire vehicle is straight at the commencement of the turn (within 0.1 metre of the entry approach tangent). In the turn the driver must steer the vehicle along the specified path. The vehicle must be steered such that the vertical projection in the ground plane of the outer most point on the outer tyre sidewall nearest to the ground[4], on the forward most outside steered-wheel, follows the specified path as illustrated below.  Using the above point as a reference, the driver must steer the vehicle along the specified path and maintain a lateral distance error between the reference point B (see below) and the specified path not greater than 50 millimetres. 

[4] This represents the outermost point on the tyre sidewall – including tyre bulge due to deflection – which is most likely to come into contact first with the kerb in a shallow angle strike.

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8 Acknowledgement

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Project partners:

#	Partner	Partner Full Name
1	MAN	MAN TRUCK & BUS AG
2	DAF	DAF Trucks NV
3	IVECO	IVECO S.p.A
4	SCANIA	SCANIA CV AB
5	VOLVO	VOLVO TECHNOLOGY AB
6	CRF	CENTRO RICERCHE FIAT SCPA
7	UNR	UNIRESEARCH BV
8	SCB	SCHMITZ CARGOBULL AG
9	VEG	VAN ECK BEESD BV
10	TIRSAN	TIRSAN TREYLER SANAYI VE TICARET A.S.
11	CREO	CREO DYNAMICS AB
12	MICH	MANUFACTURE FRANCAISE DES PNEUMATIQUES MICHELIN
13	WABCO	WABCO Europe BVBA-SPRL
14	CHALM	CHALMERS TEKNISKA HOEGSKOLA AB
15	DLR	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV
16	FHG	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
17	HAN	STICHTING HOGESCHOOL VAN ARNHEM ENNIJMEGEN HAN
18	IDIADA	IDIADA AUTOMOTIVE TECHNOLOGY SA
19	NLR	STICHTING NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM
20	TML	TRANSPORT & MOBILITY LEUVEN NV
21	TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO
22	MHH	MEDIZINISCHE HOCHSCHULE HANNOVER
23	UIRR	UNION INTERNATIONALE DES SOCIETES DE TRANSPORT COMBINE RAIL-ROUTE SCRL
24	WABCO-NL	WABCO AUTOMOTIVE BV
25	WABCO-DE	WABCO GMBH

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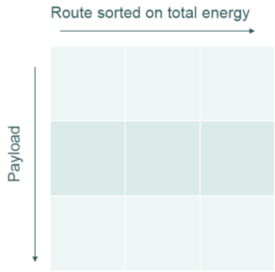
9 Appendix A – Energy and Power Demand Simulations

The hybrid sizing simulation results are given at the next pages grouped per vehicle type, e.g. TT (Section 9.1), EMS1 (Section 9.2) and EMS2 (Section 9.3). The figures are sorted based on:



- Route e.g. one drive cycle per column
- Payload e.g. one payload per row

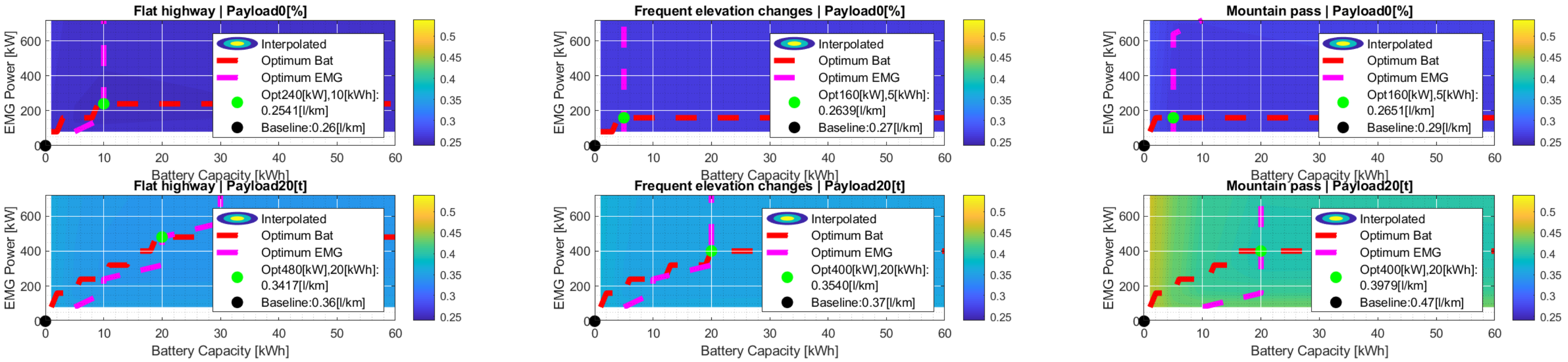
Every contour plot has the following axes:

- X-axis: Battery capacity [kWh]
- Y-axis: EMG rated power [kW]
- Z-axis: KPI of interest

9.1 Tractor Semitrailer

9.1.1 Fuel Consumption [l/km]

Fuel consumption in [l/km]Tractor semitrailer



30t Not applicable

30t Not applicable

30t Not applicable

40t Not applicable

40t Not applicable

40t Not applicable

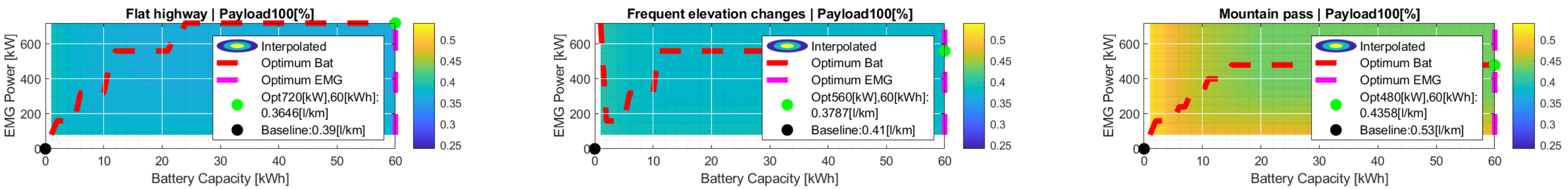


Figure 20 Fuel consumption in [l/km] for tractor semitrailer. Payloads of 30 and 40t are not admissible for tractor semitrailer due to European regulations

9.1.2 Fuel Consumption [l/tonnekm]

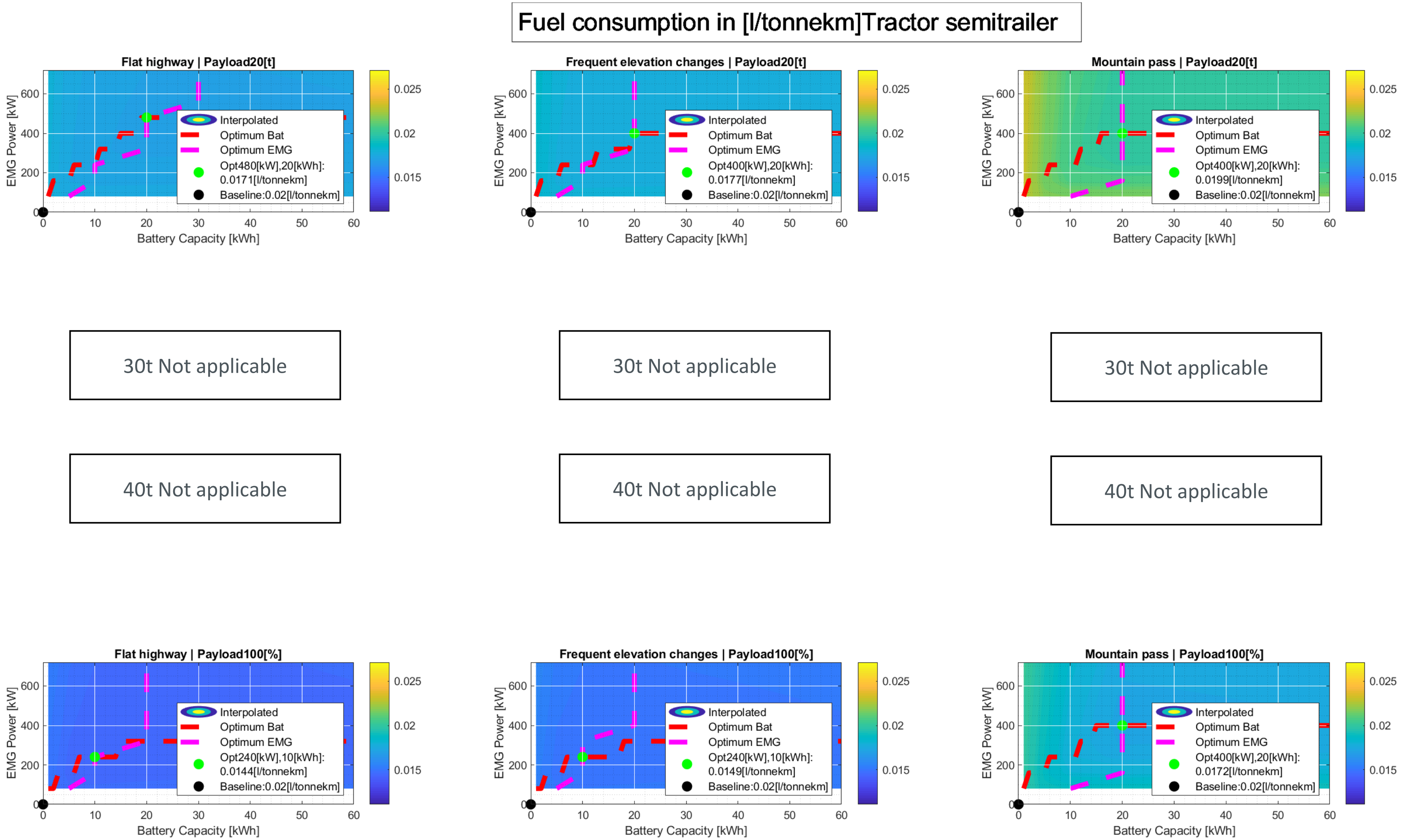


Figure 21 Fuel consumption in [l/tonnekm] for tractor semitrailer. Payloads of 30 and 40t are not admissible for tractor semitrailer due to European regulations

9.1.3 Fuel saving of [l/km]

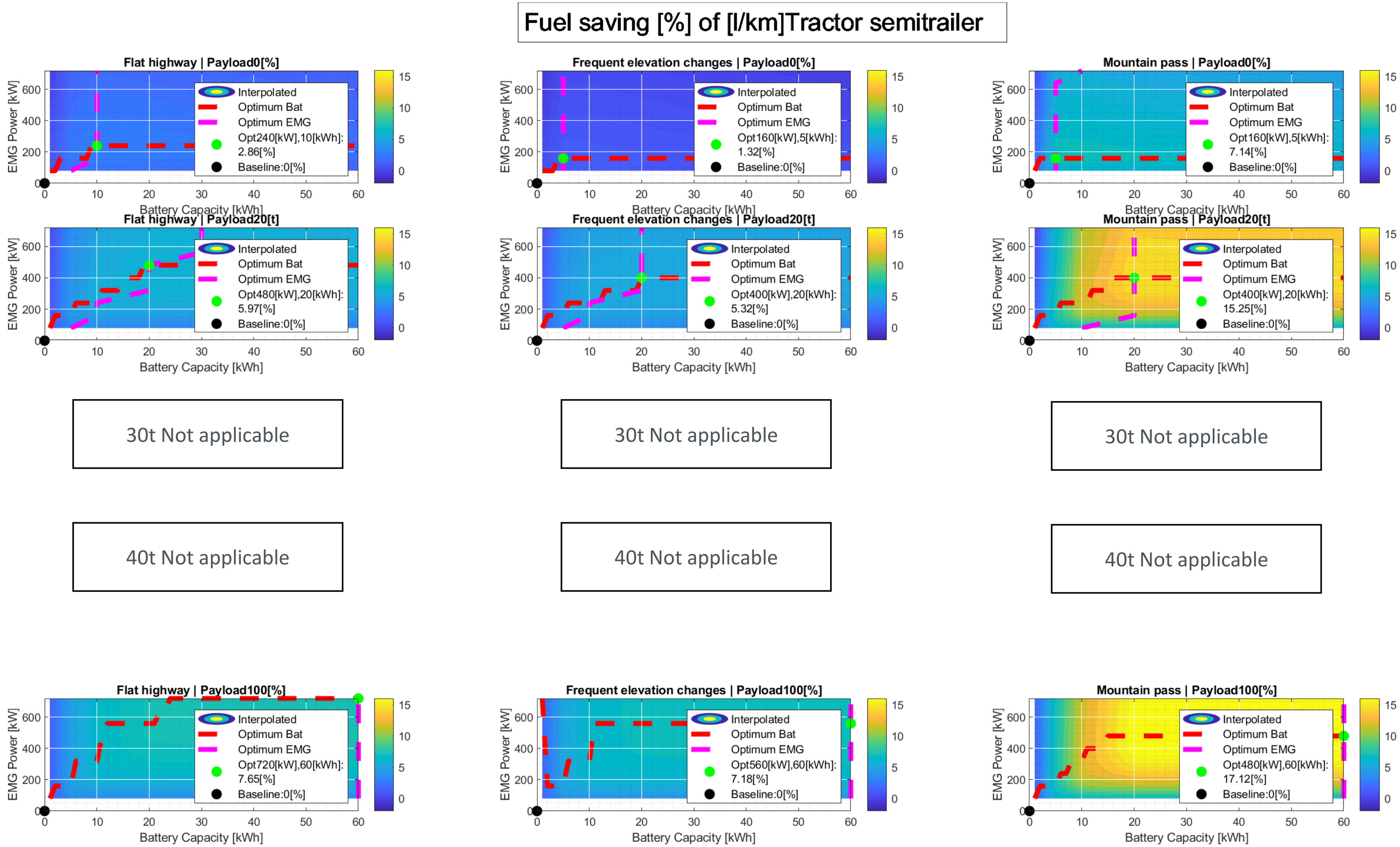


Figure 22 Saving [%] of fuel consumption in [l/km] for tractor semitrailer. Payloads of 30 and 40t are not admissible for tractor semitrailer due to European regulations

9.1.4 Fuel saving of [l/tonnekm]

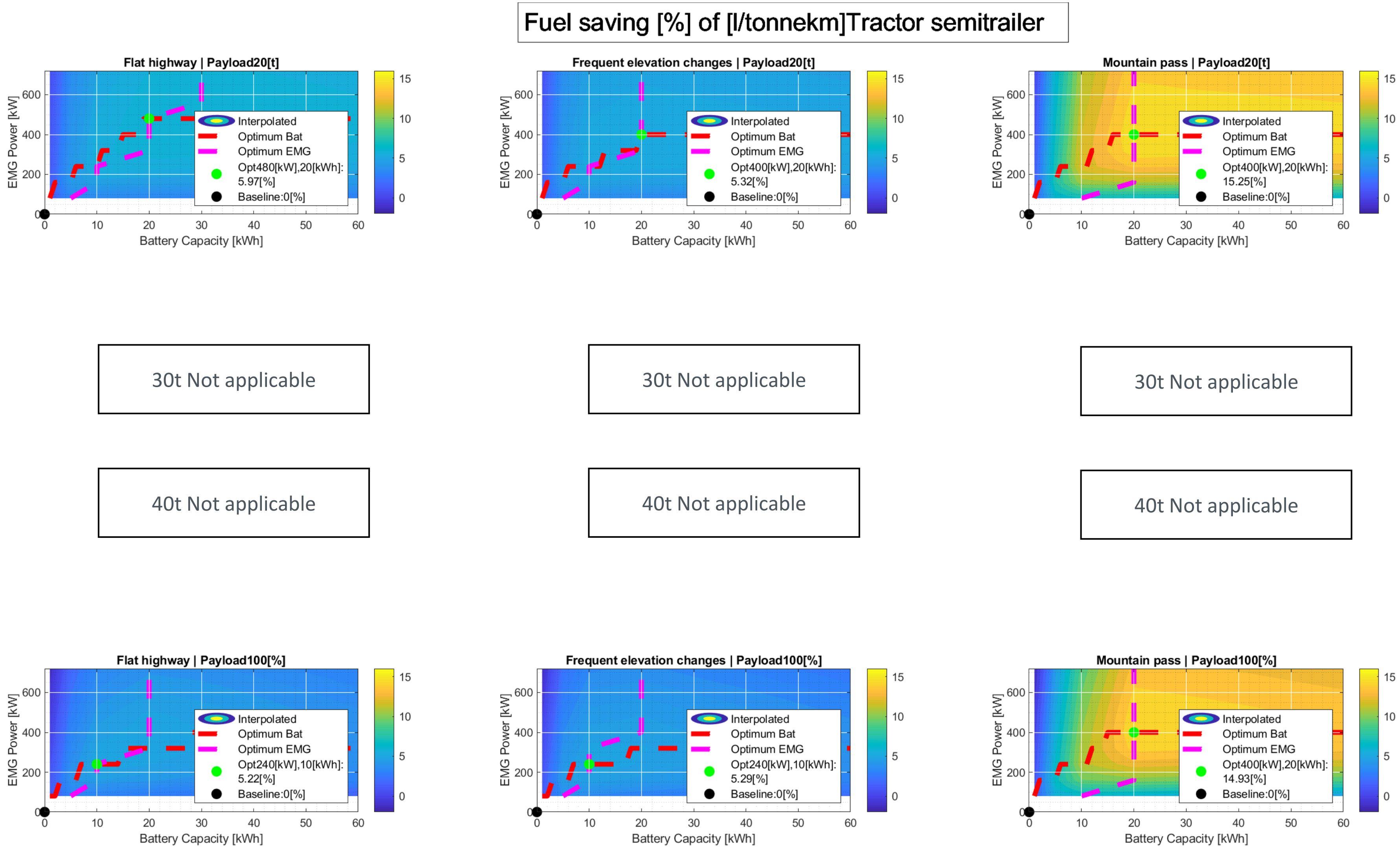


Figure 23 Saving [%] of fuel consumption in [l/tonnekm] for tractor semitrailer. Payloads of 30 and 40t are not admissible for tractor semitrailer due to European regulations

9.2 EMS1

9.2.1 Fuel Consumption [l/km]

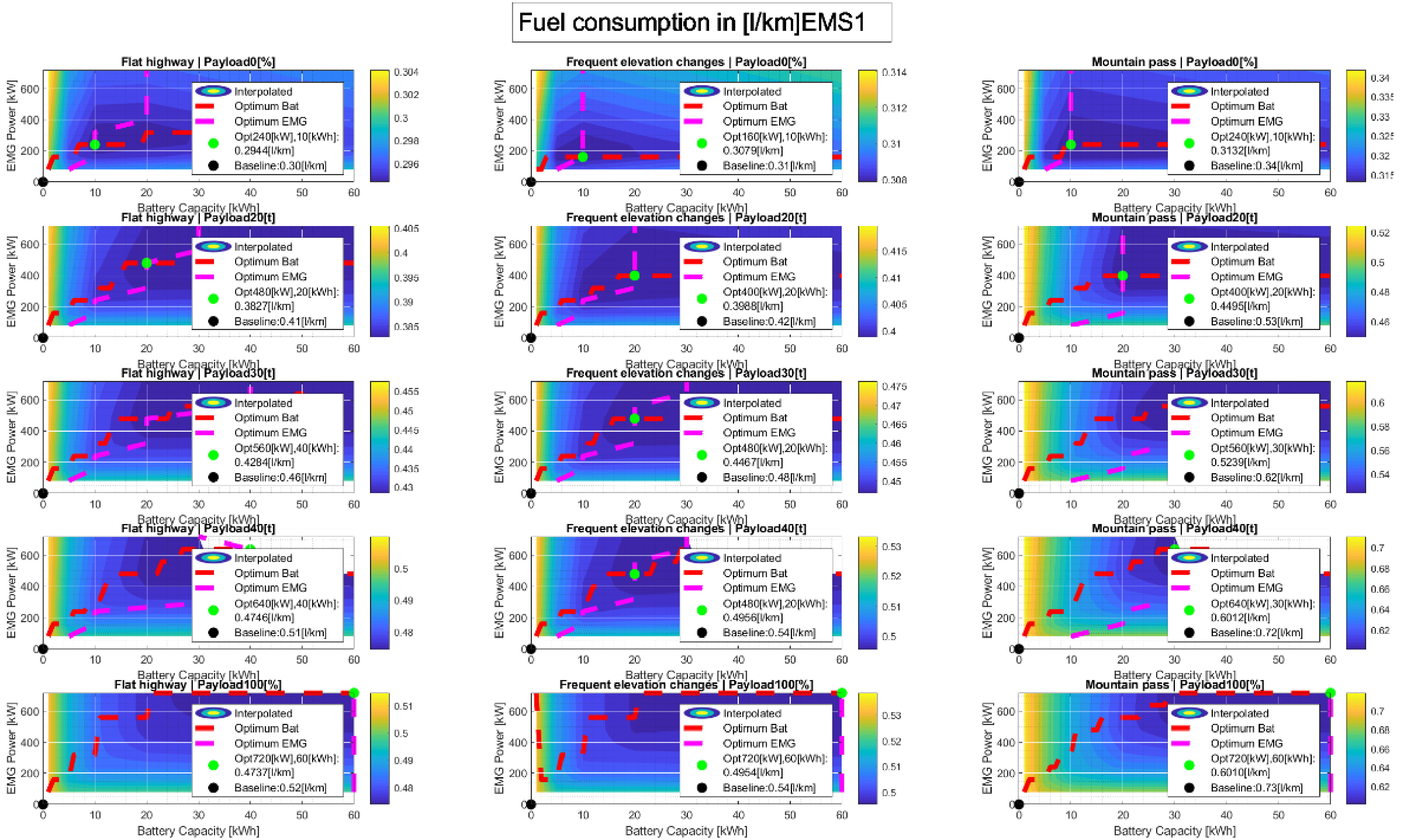


Figure 24 Fuel consumption in [l/km] for EMS1

9.2.2 Fuel Consumption [l/tonnekm]

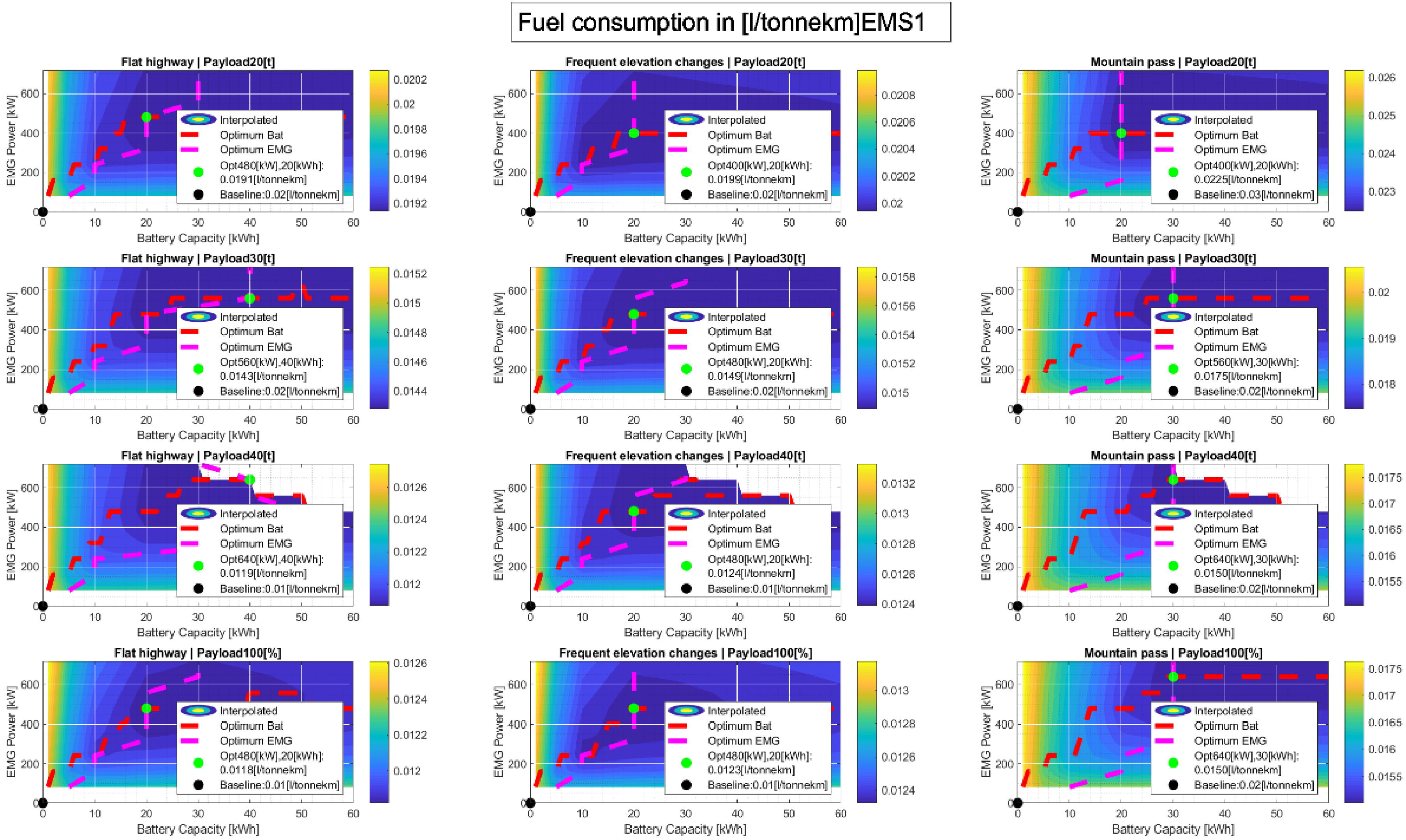


Figure 25 Fuel consumption in [l/tonnekm] for EMS1

9.2.3 Fuel saving of [l/km]

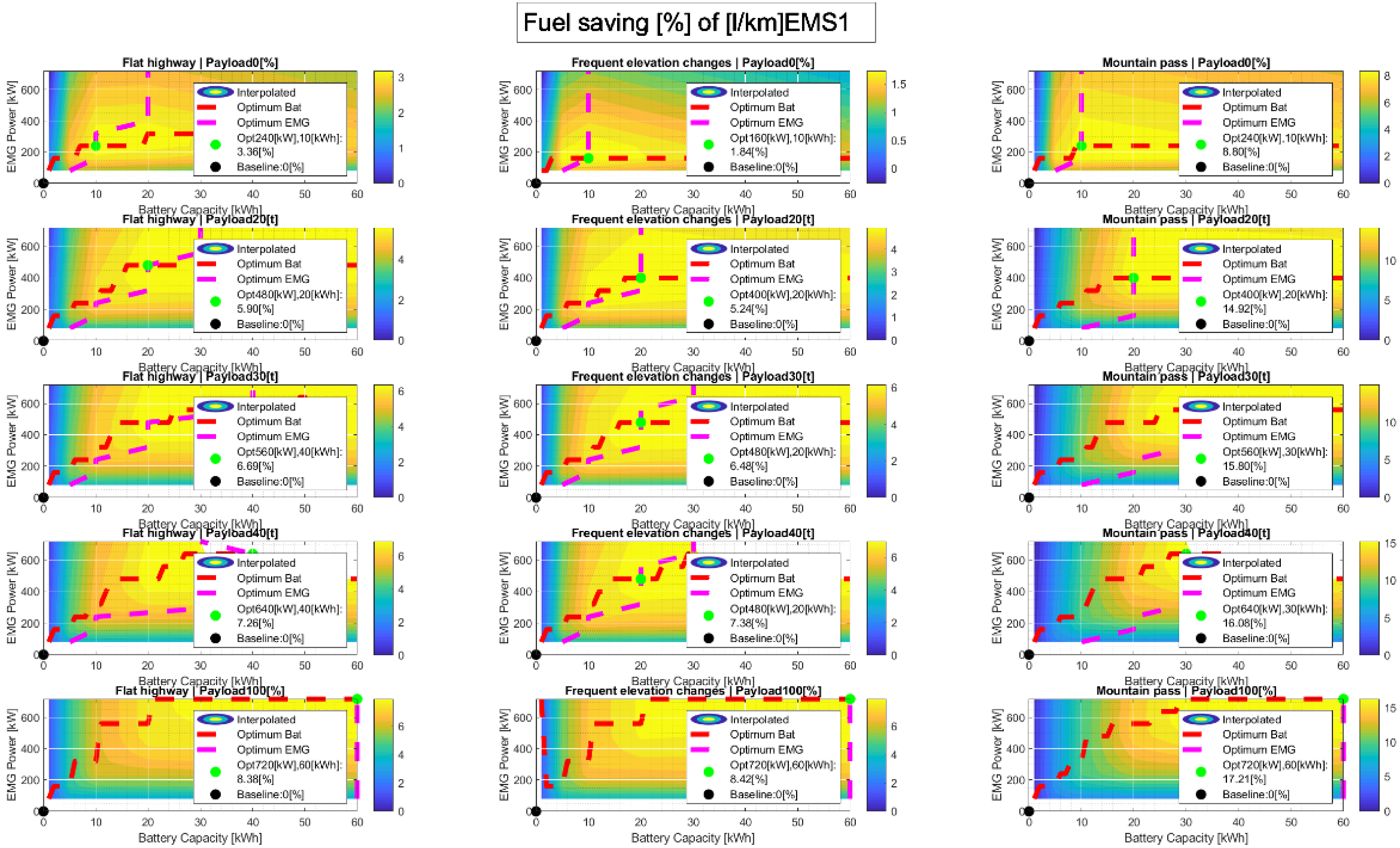


Figure 26 Saving [%] of fuel consumption in [l/km] for EMS1

9.2.4 Fuel saving of [l/tonnekm]

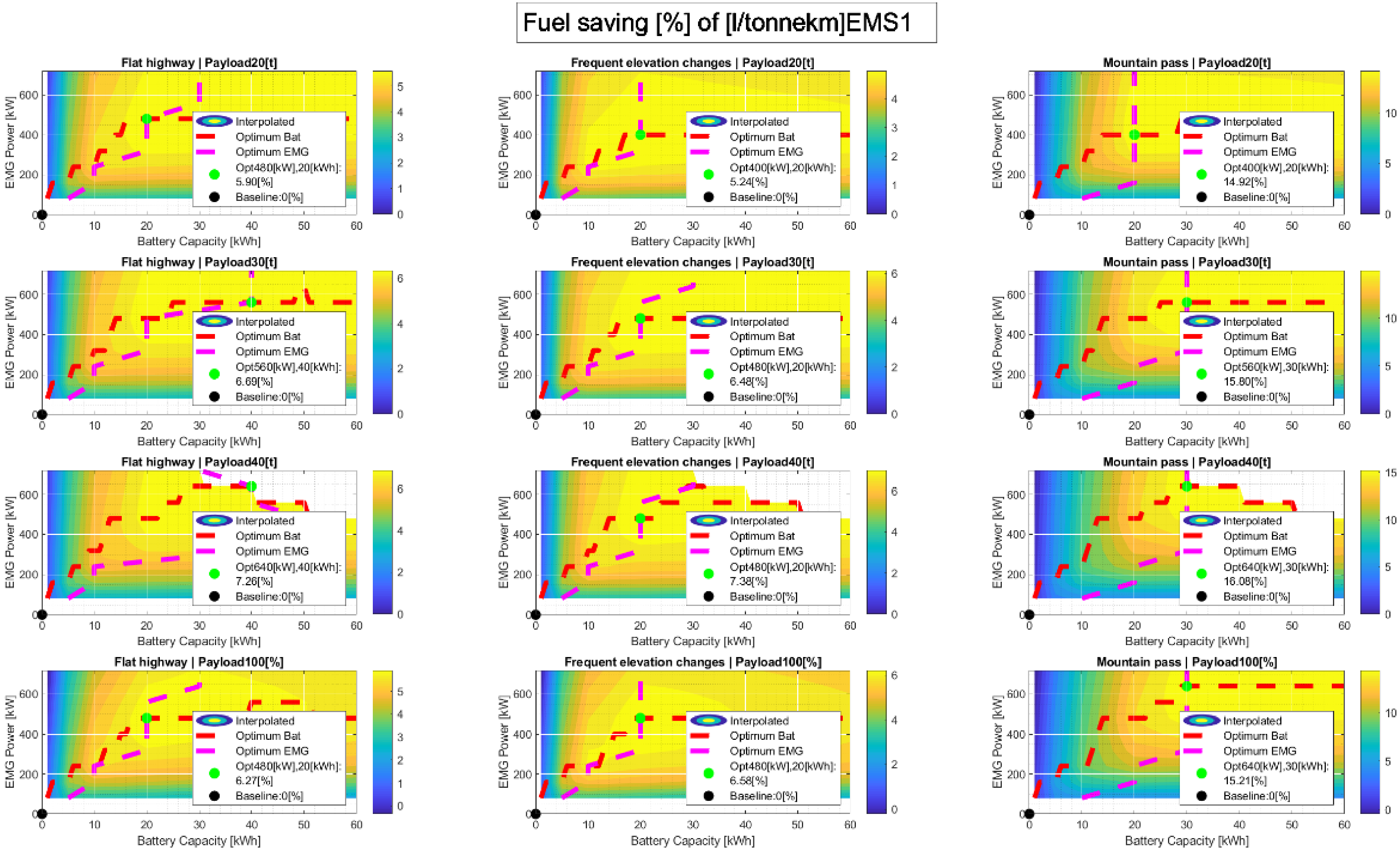


Figure 27 Saving [%] of fuel consumption in [l/tonnekm] for EMS1

9.3 EMS2

9.3.1 Fuel Consumption [l/km]

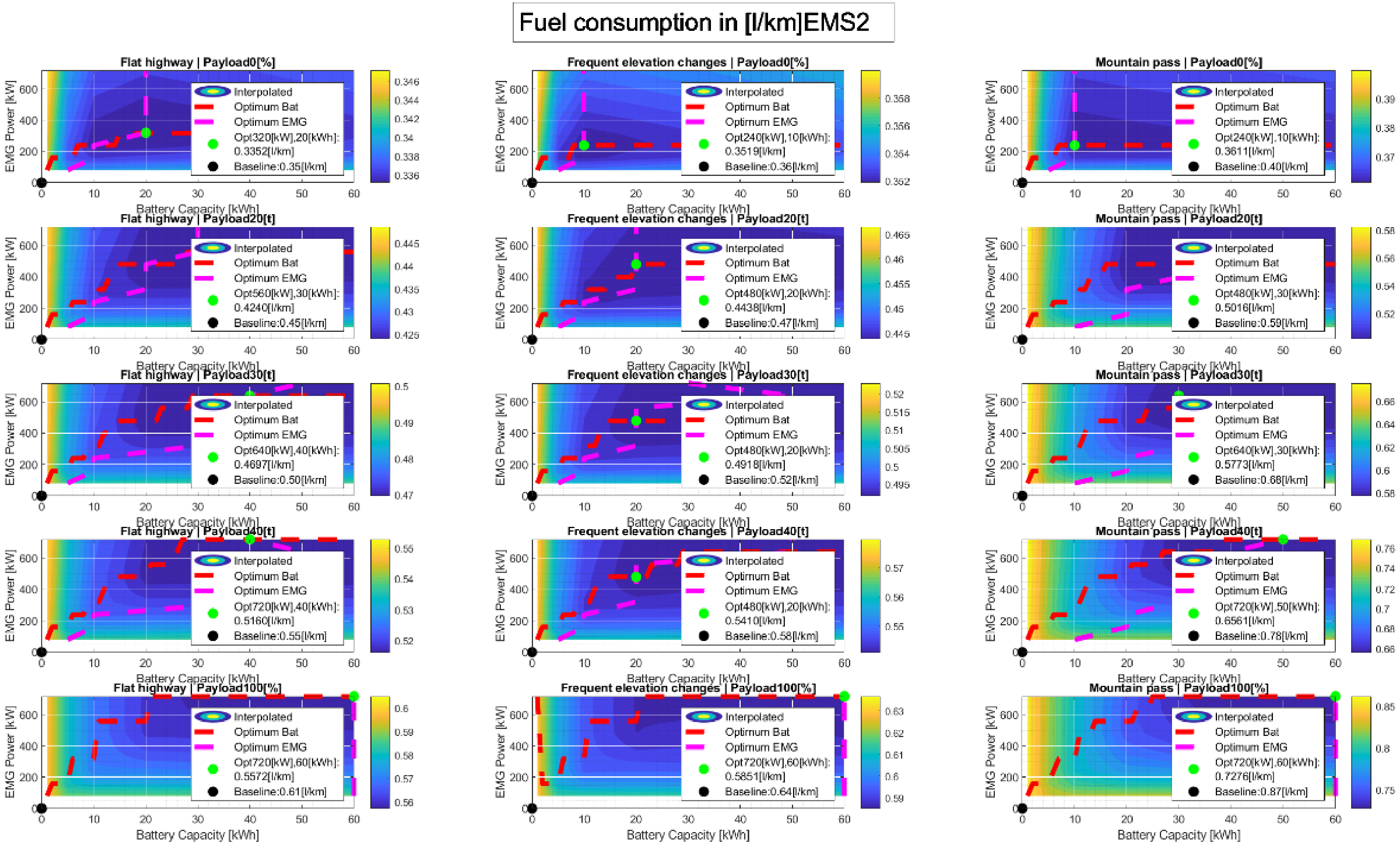


Figure 28 Fuel consumption in [l/km] for EMS2

9.3.2 Fuel Consumption [l/tonnekm]

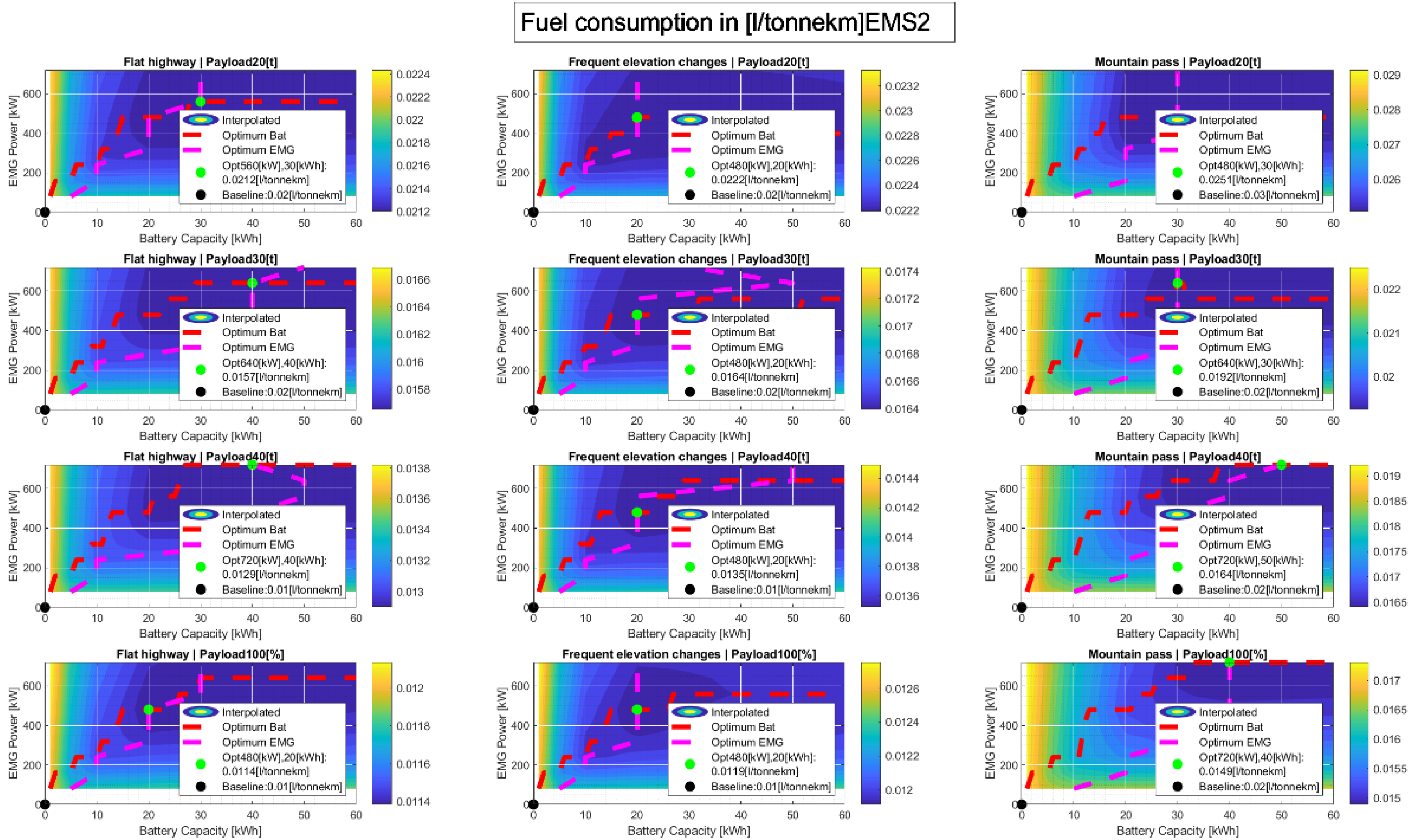


Figure 29 Fuel consumption in [l/tonnekm] for EMS2

9.3.3 Fuel saving of [l/km]

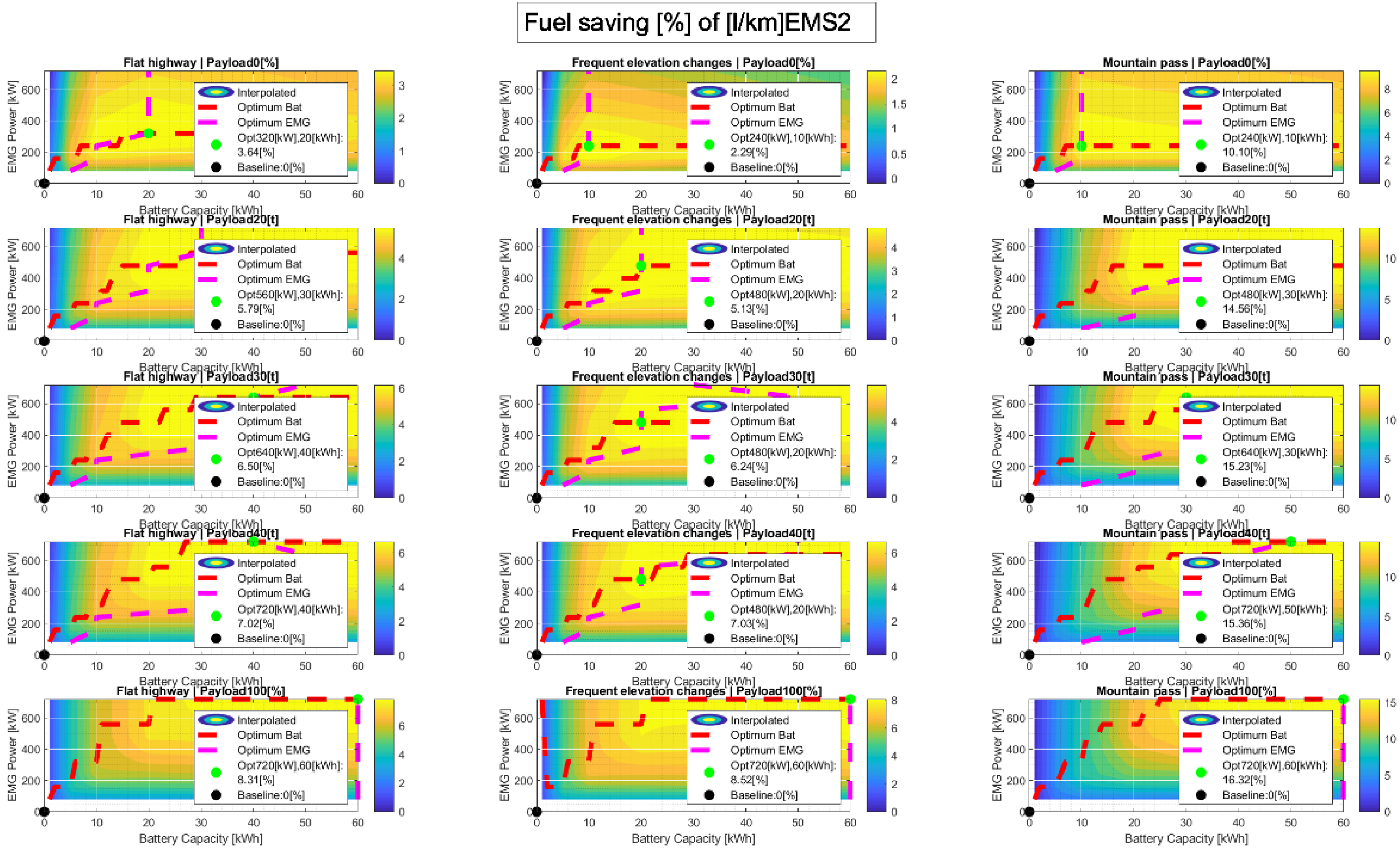


Figure 30 Saving [%] of fuel consumption in [l/km] for EMS2

9.3.4 Fuel saving of [l/tonnekm]

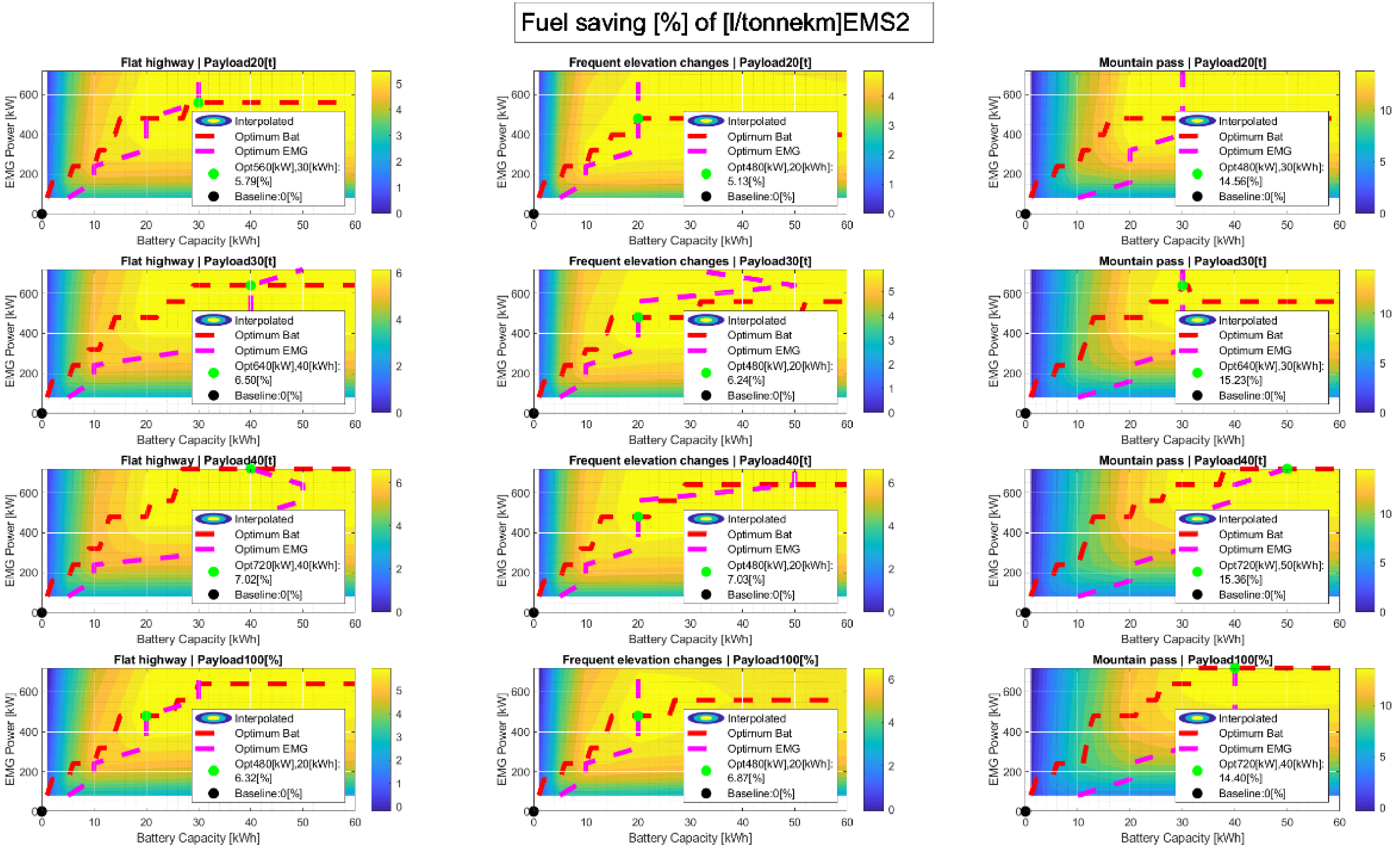


Figure 31 Saving [%] of fuel consumption in [l/tonnekm] for EMS2

10 Appendix B – List of AEMPT Requirements

In the following table all requirements for AEMPT vehicles which have been derived in this document are listed. Some requirements are linked to accordant KPIs which are then named in the last column of the table. In the course of the project, these KPIs will be assessed by measurement or simulation.

Index	Dependent from Index	Category	Requirements	Comment/KPIs
VP - 1		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to four vehicle units (up to 3 trailer units)	
VP - 2		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to 36,5m	
VP - 3		Vehicle Portfolio	An AEMPT vehicle shall be configurable of up to a GCW of 91,6 tons	
VP – 4		Vehicle Portfolio	As trailer units, an AEMPT vehicle shall be able to include full trailers, semi-trailers and dollies	
ED - 1		Energy/Power Demand	The battery capacity and electric power of an AEMPT vehicle shall allow efficiency improvements of 12% for EMS vehicles	KPIs: Fuel Consumption per 100km, Fuel Efficiency per ton-km, Average Speed
ED -2	ED - 1	Energy/Power Demand	The overall battery capacity shall be not less than 0,35kWh/ton GCW	
ED -3	ED - 1	Energy/Power Demand	The overall EMG power shall be not less than 4kW/ton GCW	
EM - 1		Energy Management	The energy management shall operate the drivetrain components efficiently to allow for high fuel savings	KPIs: Fuel Consumption in l/100km, Fuel Efficiency in l/ton-km
EM – 2	EM - 1	Energy Management	The energy management shall enable to recuperate as much energy as possible	
EM – 3	EM - 1	Energy Management	The energy management shall request torque from the electric drives in a way that allows the combustion engine to run in an efficient operating point	
EM – 4	EM -1		The energy management shall not operate the drive units in a way which increase average speed on relevant cycles	KPIs: Average Speed
EM – 5		Energy Management	The energy management shall be able to flexibly adapt to different vehicle configurations	
EM – 6	VP - 1	Energy Management	The energy management shall be able to take into account one combustion engine in combination with up to five electric drives	
EM – 7		Energy Management	The energy management shall efficiently work together with existing systems in a state of the art truck	
EM – 8		Energy Management	The energy management architecture shall have a centralized structure	
EM – 9		Energy Management	The energy management architecture shall consist of a global energy and torque management system (GETMS) and local system	

			management (LSM) instances in the trailer units.	
EM – 10		Energy Management	Each LMS shall provide information according to an AEMPT protocol to the GETMS.	
EM – 11	VP - 1	Energy Management	The communication interface should allow integrating up to five vehicle units	
EM – 12		Energy Management	An HV connector shall not be part of the AEMPT Architecture	
EM - 13		Energy Management	Applying electric torques shall not lead to an uncomfortable feeling of the driver	
VD - 1		Vehicle Dynamics	The dynamic behaviour of an AEMPT vehicle fulfil at least the requirements for conventionally driven EMS vehicles	
VD - 2	VD - 1	Vehicle Dynamics	Tracking Ability On A Straight Path shall be within 3m	KPI: Tracking Ability On A Straight Path
VD - 3	VD - 1	Vehicle Dynamics	Static Rollover Threshold shall be larger than 0,35g	KPI: Static Rollover Threshold
VD - 4	VD - 1	Vehicle Dynamics	Rearward Amplification shall be not greater than 5.7 times the static rollover threshold of the rearmost unit	KPI: Rearward Amplification
VD - 5	VD - 1	Vehicle Dynamics	High-Speed Transient Offtracking shall be smaller than 0,8m	KPI: High-Speed Transient Offtracking
VD - 6	VD - 1	Vehicle Dynamics	The Yaw Damping Coefficient shall be not less than 0.15	KPI: Yaw Damping Coefficient
VD - 7	VD - 1	Vehicle Dynamics	The vehicle shall show a minimum deceleration from 60km/h of 0.35g within a lane width of 3.0 m	KPI: Directional Stability Under Braking
VD – 8	VD - 1	Vehicle Dynamics	The steering angle gradient shall always be in the range of <tbd>	KPI: Steering Angle Gradient
VD – 9		Vehicle Dynamics	When accelerating in a curve, the vehicle shall show a stable behaviour	KPI: Cornering Stability Under Acceleration.
VD – 10		Vehicle Dynamics	When decelerating in a curve, the vehicle shall show a stable behaviour	KPI: Cornering Stability Under Deceleration.
VD – 11		Vehicle Dynamics	A vehicle dynamics controller shall limit torque requests to the electric axles in order to guarantee a stable vehicle behaviour	
VD - 12	VD- 11	Vehicle Dynamics	The vehicle dynamics controller should limit the torques of the electric axles not more than necessary for driving stability	KPI: Fuel consumtion in l/100km Restrictions on electric torques have negative effects on fuel efficiency.
VD - 13	VD- 11		The vehicle dynamics controller shall work based upon a defined list of input signals that enable it to interprete the vehicle configuration and driving situation correctly	
VD – 14		Vehicle Dynamics	The traction monitoring should not be done in the vehicle controller but locally in the traction modules	
VD - 15		Vehicle Dynamics	Anti-Lock control during recuperation should not be done in the controller but	

			locally in the traction modules	
VD - 16	VD - 12	Vehicle Dynamics	High traction at low speeds should be possible.	KPI: Acceleration Capability, Startability
VD - 17	VD - 1	Vehicle Dynamics	AEMPT vehicles shall be startable at a 12% slope	KPI: Startability
VD -18	VD - 1	Vehicle Dynamics	At least 25% of the vehicle weight shall be carried by driven axles	KPI: Acceleration Capability, Startability
VD - 19	VD - 17	Vehicle Dynamics	AEMPT vehicles up to 25,25m and up to 60ton GCW shall at least have one electrically driven axle, in addition to a conventionally driven axle.	
VD -20	VD - 17	Vehicle Dynamics	AEMPT vehicles longer than 25,25m and up to 74ton GCW shall at least have two electrically driven axle, in addition to a conventionally driven axle.	
VD -21	VD - 17	Vehicle Dynamics	For AEMPT vehicles up to 25,25m and up to 60ton GCW the wheel torque of electrically driven axles shall exceed 18000Nm at v=0km/h	
VD - 22	VD - 17	Vehicle Dynamics	For AEMPT vehicles longer than 25,25m and up to 74ton GCW the wheel torque of electrically driven axles shall exceed 30000Nm at v=0km/h, wherein for each electrically driven axle a maximum of 15000Nm is added to this value	A configuration of two axles having a torque potential of 5000Nm and 25000Nm respectively is not valid.
VD -23	VD - 1	Vehicle Dynamics	AEMPT vehicles shall be able to drive a 1% Slope continuously at 70km/h	KPI: Gradeability
VD -24	VD - 23		AEMPT vehicles up to 25,25m and up to 60ton GCW shall have a combustion engine power of at least 315kW	KPI: Gradeability, Acceleration Capability
VD -25	VD - 23		AEMPT vehicles longer than 25,25m and up to 74ton GCW shall have a combustion engine power of at least 388kW	KPI: Gradeability, Acceleration Capability