ER- TBD

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Volvo FH Long Haul Truck Electrification Feasibility Evaluation - Results

The objective of this report is to present results of a project with the purpose to evaluate the economical feasibility of hybridization of the Volvo FH long haul truck. In the study a conventional powertrain is compared to a strong hybrid powertrain. Strong means that significant (5-30%) fuel consumption reduction is possible. To sort out a competitive hybrid powertrain variants, two engine sizes, three battery sizes, different battery depth of discharge levels are evaluated. The battery sizes ranges from 5-90 kWh useful energy. In addition, plugin hybrid variants are included; these use grid energy by night charging.

To avoid cycle beating, i.e. drawing rash conclusions from a single transport task, ~20 driving cycles are considered. These are categorized into flat, predominantly flat, hilly and the LH0 collective. To make future predictions for the choice of powertrain technology a set of years (2020, 2025,2030) are studied. To enable more general conclusions, a sensitivity study, varying for example battery and fuel price evolution, is also carried out. The sensitivity study focuses on the most competitive hybrid powertrain variant, its ownership cost is compared to the ownership cost of a conventional powertrain. Following conclusions are made:

- By utilizing sophisticated predictive energy management, significant fuel consumption reduction, 10-30% depending on transport task, is possible for Volvo FH hybrid trucks. The major explanation is that a long prediction horizon enables extensive regeneration of potential energy. The energy management control can prepare the battery energy level for coming down and uphill situations in such a way that energy wasting, for example engine braking, is minimized.
- The ownership cost is probably at least ~2% better for hybrid Volvo FH trucks compared to conventional Volvo FDH truck. This is valid for most European countries after 2020. The difference is up to 15% for a FH truck bought after 2030. This indicates that a paradigm shift in propulsion of long haul trucks could start up after ~2020.
- The purchase price of a strong hybrid Volvo FH is 30-60 kEuro higher compared to the conventional trucks.
- The ownership cost of the plugin hybrid is lower compared to the hybrid. The explanation is that reduction in fuel consumption cost, due to grid energy, is higher than the added electricity and battery degradation cost.
- An appropriate battery energy capacity is 5-50 kWh. The indication is that an energy optimized LiIon battery is suitable. Further studies are needed to identify a more exact value and cell type.
- Fuel price and battery cost (Euro/kWh) are two very important parameters for the cost efficiency of strong hybrid Volvo FH trucks. Electricity price has a minor influence.
- For scenarios with no fuel price increase from 2015, i.e. always 1.28 Euro/liter, and battery prices unchanged from 2015, hybrid Volvo FH trucks will have a TCO higher compared to conventional Volvo FH trucks.

Contents

1. References

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[4] http://www.fuel-prices-europe.info/

[5] P. Klintbom, “Diesel Fuel Price & Supply 2009-2030”, report no 06150-09-13788-1, VTEC, 2009.

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2. Terms

Table 1. Terms

Term	Description
Hybrid Electric Vehicle	A road vehicle that can draw propulsion energy from both of the following on-vehicle sources of stored energy: 1) one or more consumable fuels and 2) one or more energy storage systems that is/are recharged by an electric motor-generator system, an off-vehicle electrical energy source, or both.
Plug-in Hybrid Electric Vehicle	A hybrid electric vehicle with the ability to store and use off-board electrical energy in at least one of the energy storage systems. Off-board energy is handled by charging poles.
Slide-in Hybrid Electric Vehicle	A hybrid electric vehicle with the ability to store and use off-board electrical energy in at least one of the energy storage systems. In contrast to plug-in vehicles, slide in vehicles can be charged also when running.
TCO	Total Cost of Ownership
AMT-PS	Automatic Mechanically engaged Transmission with Power Shift function
EM	Electric Machine
HCVT	Hydraulic Continuously Variable Transmission.
ECVT	Electric Continuously Variable Transmission.

3. Scope definition

One purpose of this chapter is to provide a motivation for the study. Another is to identify requirements. The actual solutions are not considered at all in this chapter.

Business opportunity identification

The majority of Volvo Group revenue is from long haul trucks. Hence, it is vital to study, know and understand when and if it is cost efficient to utilize a secondary power source device in these vehicles. Examples of secondary power sources are combustion engines and batteries. A battery has the ability to capture potential and kinetic energy.

Project objective

The objective is to evaluate the use of a secondary power source in Volvo FH for different transport tasks, operating in terrain with more or less shifting altitude. The evaluation will be made by minimizing total ownership cost. Predictive control will be a vital ingredient in the study.

Study setup

Table 2 presents the the study setup. The setting variants marked by (secondary) are performed only if project time and resources allows, their priority is lower. In Appendix 29 the powertrain layouts are illustrated.

Table 2. Studied settings.

Setting	Variant	Comment
Powertrain topology	• Conventional • Electric hybrid AMT-PS • Electric hybrid HCVT (secondary) • Dual engine hybrid (secondary) • Slide in (secondary)	Powertrain type. The Dual engine hybrid has a specific transmission. HCVT is hydraulic CVT transmission. These transmissions are relevant for the electric hybrid topology.
Engine variants	• MD13 • MD8 (3 cyl) • MD5 (Eu6)	Each engine corresponds to different power, torque and efficiency data. Engine comb={MD8,MD5} and {MD13,MD8}/{MD13,MD5} (secondary)
Battery sizes	• ~5 kWh • ~50 kWh • ~90 kWh	Only relevant for electric hybrid. Must handle 150 kW. Minimum mass. For every battery size, there are three different depth of discharge levels evaluated.
Charging scheme	• Plugin. Enable external grid charging • Hybrid. No external grid charging	External grid charging, not relevant for dual engine hybrid, imply that start state of charge is close to one and end state of charge is free of choice (probably close to zero). No external grid charging gives that end start of charge must be large or similar to start state of charge.
Transport task types	• Flat • Predominantly flat • Hilly • LH01 (in revised version)	See Appendix 29 for detailed definition. Approximately 80% of real world operation is predominantly flat, hence this type is divided into two sub types.

4. Analysis process overview

In Figure 1 the analysis process is illustrated. The most demanding phase is “Use predictive and power split optimization based method to simulate fuel cons etc”. The phase includes methods developed in [3].

As presented in the figure several SoC swings are evaluated. Broadly speaking this means that is is analyzed if a battery should be deeply charged/discharged or just shallow battery cycles shall be utilized. This is described more in detail in “Handling the depth of discharge influence on battery degradation” in [1].

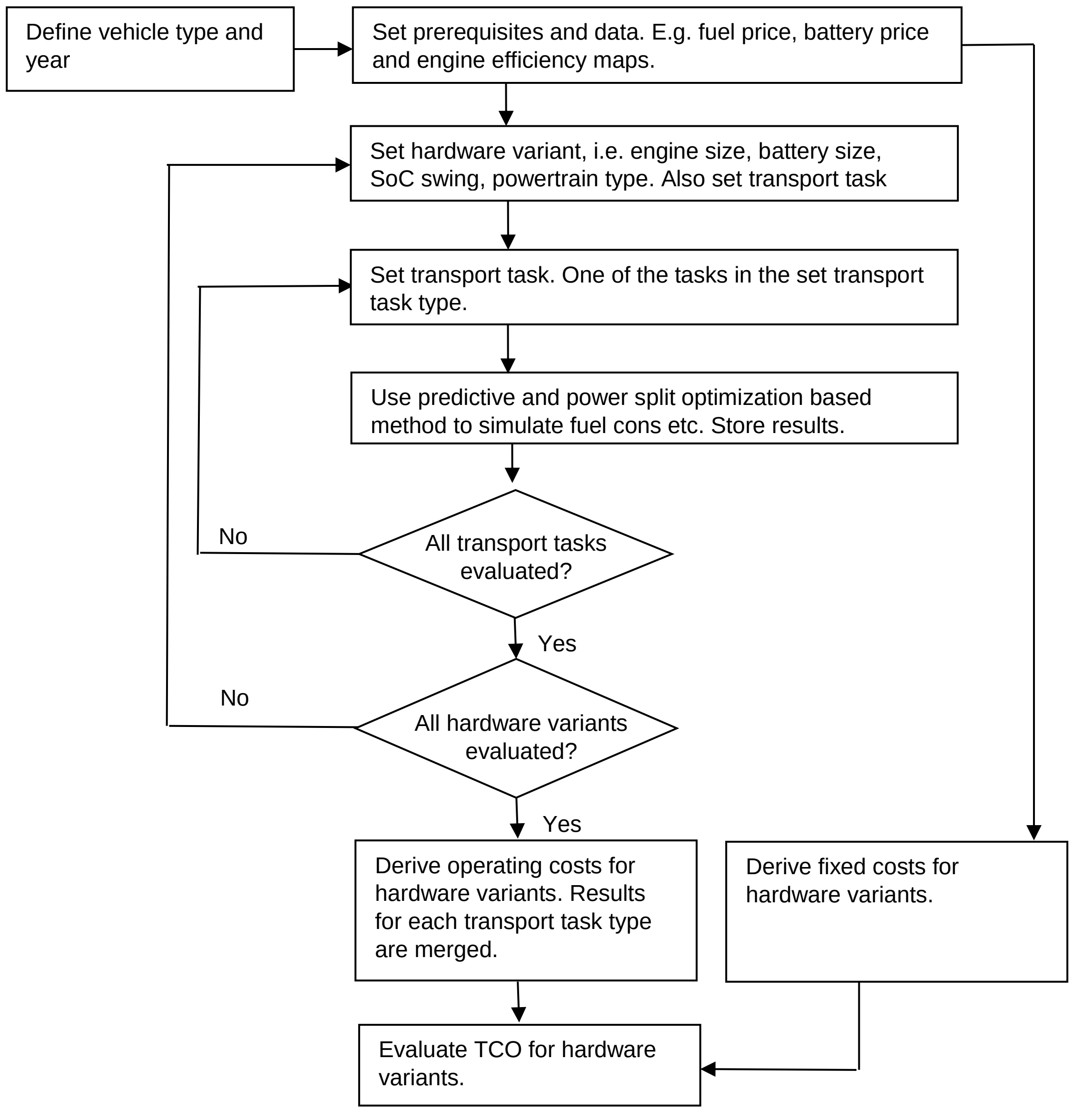
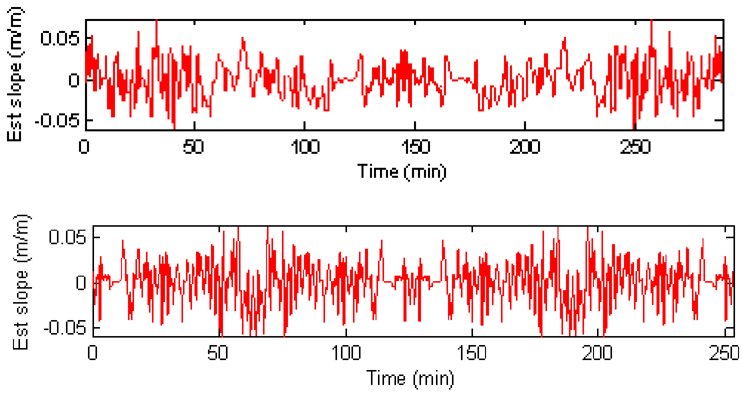


Figure 1. *Analysis process for long haul hybrid feasibility study.*

5. Potential regeneration power of a truck running downhill

This chapter analysis the maximum power that can be regenerated when a truck runs downhill. A motivation for this is to ensure that there is high enough power available when running downhill. Figure 2 motivates that slopes typically varies between 1 and 5%. Both the example profiles are of the predominantly flat type. For the most common type, predominantly flat, the slope is more than 3% for a significant part (0-20%) of the transport task.



Topography	Slope		
	<3%	<6%	<9%
FLAT	>98%		
PFLAT	>80%	>98%	
HILLY	>65%	>90%	>98%

Figure 2. *Slope profile examples. Sx135FrankfurtKoblenz (Top). Sx096GöteborgAlingsås (below). Topography classification (right)*

Figure 3 presents forces affecting a truck. It also defines the slope, in this case negative. In (1)-(3) these forces are related to the power demand when going downhill.

$$(1)\quad P_{\mathrm{dem}} = T_{\mathrm{prop}} \cdot \omega_{\mathrm{wheel}} \cdot \eta_{\mathrm{transm}} + P_{\mathrm{aux}} \qquad \omega_{\mathrm{wheel}} = v / R_{\mathrm{w}}$$

$$(2)\quad T_{\mathrm{prop}} = \left(m \cdot a + F_{\mathrm{res}}\right) \cdot R_{\mathrm{w}}$$

$$(3)\quad F_{\mathrm{res}} = f \cdot m \cdot g \cdot \cos(\varphi) + m \cdot g \cdot \sin(\varphi) + \frac{1}{2} \cdot \delta \cdot CdA \cdot v^2 \qquad \varphi = \tan(slope)$$

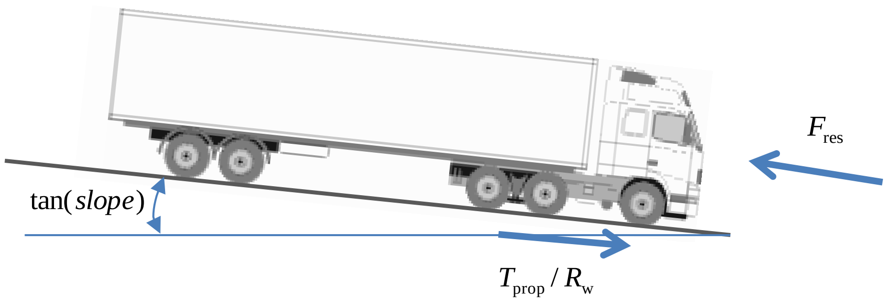
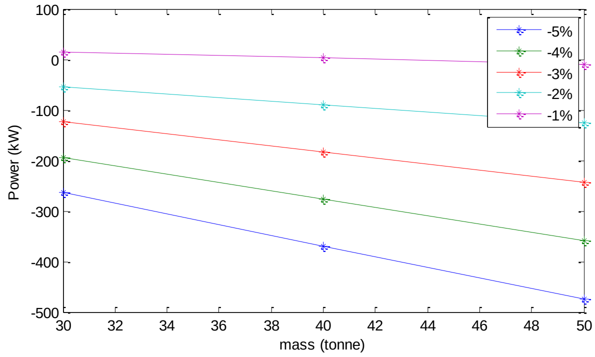


Figure 3. *Forces affecting a truck.*

Table 3 presents parameters for the results presented in Figure 4. It shall be stressed that the deceleration is zero. As the figure shows, approximately 120 kW excess traction power is available when a long haul trucks runs downhill in a 2-3% slope. The figure also shows that when a light truck runs downhill no or just a few tens of kW is available. The reflection shall be that regeneration of potential energy is important for heavy trucks but not for light trucks.

Table 3. Parameter setting.

Term	Value	Comment
P_{aux}	3 kW	Auxiliary power
η_{transm}	0.95	Transmission efficiency
a	0	Acceleration.
R_{w}	0.49 m	Wheel radius
δ	1.3 kg/m^3	Air density
CdA	5.14 m^2	Air drag coefficient
f	0.0047	Rolling resistance coefficient
v	80/3.6 m/s	Vehicle speed



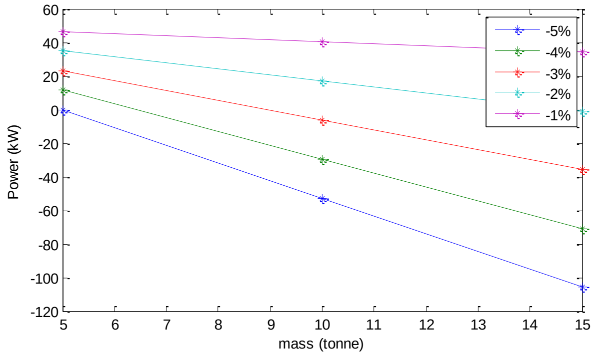


Figure 4. *Results. Power demand. FH long haul truck (left), FL city distribution truck (right).*

6. Total cost of ownership evaluation

This chapter presents equations for evaluating the total cost of ownership for hybrid, plugin and conventional vehicle topologies.

Hybrid vehicle cost function

In (1)-(6) equations for evaluating the TCO for hybrid vehicle is presented. Terms are described in Table 4.

(1) $TCO^{hybrid} = c_{fix}^{hybrid} + c_{oper}^{hybrid}$

(2) $c_{oper}^{hybrid} = c_{\mathrm{batt}} \cdot \mu_{battrepl}^{econ} + c_{\mathrm{fc}} + c_{\mathrm{el}}$

(3) $p_{purch}^{hybrid} =$

$$markup \cdot (p_{\mathrm{chass}} + p_{\mathrm{eng}} + p_{\mathrm{trans}} + p_{\mathrm{finalgear}} + p_{\mathrm{eladdon}} + p_{\mathrm{em}} + p_{\mathrm{batt}} + p_{\mathrm{masspen}})$$

(4) $c_{fix}^{hybrid} = annuit(p_{\mathrm{hybrid\ purch}})/L_{\mathrm{peryear}}$

(5) $c_{\mathrm{batt}} = annuit(p_{\mathrm{batt}})/L_{\mathrm{peryear}}$

(6) $annuit(p) = (\frac{R}{(1+r)^L} - p) \cdot \frac{r}{1-(1+r)^{-L}}$

Table 4. Term descripton.

Parameter	Description
TCO	Total Cost of Ownership (Euro/km)
c_{xx}	Cost (Euro/km) of component or measure xx.
$\mu_{battrepl}^{econ}$	Number of battery replacements during first owner lifespan T^{econ}.
p_{xx}	Price (Euro) of component xx.
$p_{\mathrm{xx\ purch}}$	Purchace price (Euro). The price the customer experience for purchasing the vehicle.
markup	A markup factor is used to handle that the purchase price is higher than the production cost.
L_{peryear}	Yearly travelled distance.
R, L, r	R is restvalue after L, L is the number of years the first owner use the vehicle, r is interest rate.
$p_{\mathrm{eladdon}}, p_{\mathrm{em}}, p_{\mathrm{masspen}}$	Add on price for electrification (e.g. the price of electric auxiliary systems), price of electric machine and mass penalty. Mass penalty relates to increased mass shall be compensated by low weight design.
$annuit$	The conversion between price (€) and cost (€/year) is done by an annuity calculation.
c_{masspen}	A cost term reflecting that decreased payload lowers vehicle productivity. The mass cost penalty is based on the reasoning that a light-weight construction has a specific cost per kg. See [2] for details.

Plugin vehicle cost function

One difference between the hybrid variant and plugin variant is that electricity cost is relevant for the plugin vehicle because it utilizes grid energy when it charges the battery (usually at night). The electricity taken from the grid to propel the plugin vehicle is converted to corresponding fuel consumption, $m_{\text{fuel}}^{\text{plugin}}$. The fuel consumption for the plugin variant is then achieved according to:

$$(7)\ m_{\text{fuel}}^{\text{plugin}} = m_{\text{fuel}}^{\text{hybrid}} - m_{\text{fuel}}^{\text{grid}}$$
$$(8)\ m_{\text{fuel}}^{\text{grid}} = E_{grid} \cdot \frac{1}{Q_{fuel} \cdot \eta_{eng}}$$
$$(9)\ c_{fc}^{plugin} = m_{\text{fuel}}^{\text{grid}} \cdot price_{fuel}$$

Where E_{grid} is the energy charged from the grid, Q_{fuel} is the fuel heat value (J/kg). The fix cost for the plugin variant is assumed to be the same as for the hybrid.

$$(10) \qquad p_{purch}^{plugin} = p_{purch}^{hybrid}$$

Evaluation of number of battery replacements during economic lifetime

The number of battery replacements during the technical vehicle lifetime T^{tech} is given by (11). Figure 5 plots the function. A consequence of the relations is that if the battery degradation is lower than 1, during T^{tech}, no battery replacement is needed.

$$(11) \qquad \mu_{battrepl}^{tech} = floor(\Delta SoH^{tech})$$

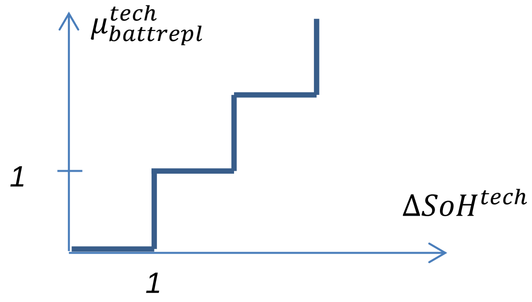


Figure 5. *Number of battery replacements during technical lifetime.*

Equation (12) expresses how the number of battery replacements during technical lifetime is related to the number of battery replacements during economic lifetime. In (13) battery degradation during technical lifetime is related battery degradation during economic lifetime. By combining (11)-(13), equation (14) is derived. The equation relates battery degradation during economic lifetime to the number of battery replacements during economical lifetime. It can be expressed as that the battery must degrade slower than the vehicle if battery replacement shall be avoided.

$$(12) \qquad \mu_{battrepl}^{econ} = \mu_{battrepl}^{tech} \cdot \frac{T^{econ}}{T^{tech}}$$

$$(13) \qquad \Delta SoH^{tech} = \Delta SoH^{econ} \cdot \frac{T^{tech}}{T^{econ}}$$

$$(14) \qquad \mu_{battrepl}^{econ} = \text{floor}(\Delta SoH^{econ} \cdot \frac{T^{tech}}{T^{econ}}) \cdot \frac{T^{econ}}{T^{tech}}$$

To improve the understanding of these relations, Table 5-Table 7 present the relation between ΔSoH^{econ} and $\mu_{battrepl}^{econ}$ for different settings of T^{tech} and T^{econ}.

Table 5. Number of battery replacements during economic lifetime. T^{tech}=10, T^{econ}=10.

ΔSoH^{econ}	ΔSoH^{tech}	$\mu_{battrepl}^{tech}$	$\mu_{battrepl}^{econ}$
0.45	0.45	0	0
0.55	0.55	0	0

1.1	1.1	1	1

Table 6. Number of battery replacements during economic lifetime. T^{tech}=10, T^{econ}=5.

ΔSoH^{econ}	ΔSoH^{tech}	$\mu_{battrepl}^{tech}$	$\mu_{battrepl}^{econ}$
0.45	0.9	0	0
0.55	1.1	1	0.5
1.1	2.2	2	1

Table 7. Number of battery replacements during economic lifetime. T^{tech}=10, T^{econ}=1.

ΔSoH^{econ}	ΔSoH^{tech}	$\mu_{battrepl}^{tech}$	$\mu_{battrepl}^{econ}$
0.09	0.9	0	0
0.11	1.1	1	0.5
0.61	6.1	6	0.6

Conventional vehicle cost function

In (15)-(19) equations for evaluating the TCO for hybrid and plugin vehicle is presented. As (16) shows, fuel consumption is the only operation cost.

(15) $$TCO_{\mathrm{conv}} = c_{\mathrm{conv\ fix}} + c_{\mathrm{conv\ oper}}$$

(16) $$c_{\mathrm{conv\ oper}} = c_{\mathrm{fc}}$$

(17) $$p_{\mathrm{conv\ purch}} =$$

(18) $$markup \cdot (p_{\mathrm{chass}} + p_{\mathrm{eng}} + p_{\mathrm{trans}} + p_{\mathrm{finalgear}})$$

(19) $$c_{\mathrm{conv\ fix}} = annuit(p_{\mathrm{conv\ purch}})/L_{\mathrm{peryear}}$$

7. Energy management strategy

The energy management strategy in a hybrid vehicle, primary determines the power/torque split between the engine and the electric drive. Implicitly, the battery energy level is set from this split. The following example constraints, on an energy management strategy, must normally be handled:

- Power and torque restrictions of the engine, electric machine and battery cannot be violated.
- The battery is not allowed to be drained or over charged.
- Fuel consumption/battery degradation/electric drive energy losses shall be minimized.
- Vehicle stability must to be risked, this is further described in [8].

If the energy management strategy is “not good enough”, i.e. too simple, properties such as fuel consumption, battery degradation rate etc, will not make a hybrid competitive. Imagine for example an extreme case with a really poor strategy that implies that the battery shall not be used at all (engine power corresponding to traction power), in such a case the expensive hybrid powertrain will make the hybrid heavier and hence less fuel efficient compared to a conventional vehicle. The consequence from this reasoning is that for the evaluation of a hybrid vehicle the energy management strategy is critical.

Types of energy management strategies for hybrids

Table 8 presents different aspects for describing the character of an energy management strategy. It also presents the character of the strategy used in this study, a strategy that is further described in [3]. The concept of predictive control, very important for this study, is explained further in Appendix 19.

Table 8. Energy management strategies.

Aspect	**Description**	**Used in this study**
Rule or model based.	Examples of rule-based methods are neural networks and fuzzy logic. Model based methods uses a mathematical (state space formulization) described plant model to derive control signals.	Model based
Predictive or non-predictive	Predictive strategies needs future information, for example the estimated vehicle power need. The future information can be guessed or derived from a “intelligence gathering system”, for example a camera. Non-predictive just uses the present information.	Predictive
Length of prediction horizon	Full or partial. Seconds, minutes or hours.	2-3 hours
Minimization function	Fuel, wasted energy, battery wear or combinations of these are examples of possible objective functions.	Operating cost
Hybrid or plugin hybrid	If grid power is fed into a hybrid vehicle, it is a plugin hybrid. In such case a charge depleting control strategy is needed. It means that the battery energy level in the end of transport task shall be lower than in the beginning.	Hybrid and plugin hybrid
Adaptive or non-adaptive	An adaptive control automatically adapts its behavior during vehicle operation. One can for example think of a strategy that uses less battery power if the battery health is bad. This aspect is a bit vague and much coupled to if a control is model based or not. Updating a parameter, for example battery capacity, in the plant model of a model-based strategy will make it adaptive.	Non adaptive

8. Performance evaluation

Table 9 presents the performance results. The Boolean variable ‘perfok’ specifies it a variant is accepted. The variant ‘ConvMD13AMTps’ shall be regarded as acceptable despite its value of perfok. The reason is that gradeability is failed with a very small marginal. The important interpretation of the table is that most variants with some of the two smaller engines {MD5,MD8} not are feasible from a performance perspective. Hence, these can be sorted out from the coming cost analysis. The method is described in [1].

Table 9. Performance evaluation results.

Pwtname	maxv1deg (kph)	Pbgrade (kW)	maxv0deg (kph)	Peldrivetopspeed (kW)	perfok
ConvMD13AMTps	88	6	139	0	0
DualengMD8&MD5Hcvt	95	0	145	0	1
ElhybMD13AMTpsBs1	88	6	139	0	1
ElhybMD13AMTpsBs2	88	6	139	0	1
ElhybMD13AMTpsBs3	88	6	139	0	1
ElhybMD13HcvtBs1	86	14	137	0	0
ElhybMD13HcvtBs2	86	14	137	0	1
ElhybMD13HcvtBs3	86	14	137	0	1
ElhybMD8AMTpsBs1	62	101	115	17	0
ElhybMD8AMTpsBs2	62	101	115	17	0
ElhybMD8AMTpsBs3	62	101	115	17	1
ElhybMD8HcvtBs1	61	107	114	22	0
ElhybMD8HcvtBs2	61	107	114	22	0
ElhybMD8HcvtBs3	61	107	114	22	1
ElhybMD5AMTpsBs1	50	139	103	55	0
ElhybMD5AMTpsBs2	50	139	103	55	0
ElhybMD5AMTpsBs3	50	139	103	55	1
ElhybMD5HcvtBs1	49	143	101	59	0
ElhybMD5HcvtBs2	49	143	101	59	0
ElhybMD5HcvtBs3	49	143	101	59	1

9. Assumptions

Following assumptions was used for a first simulation run presented in Chapter 10-12. Chapter 13-16 presents revised results. For example is the yearly travelled distance below to low and therefore changed in the revised analysis.

- Only the first user is regarded. Hence the economic lifetime is 5 years.
- Prerequisites, e.g. fuel and battery price, are set for average year of the first user. With production years 2020 and 2025, prerequisites are set for 2022 and 2027.
- The *SoC* is not allowed to be higher than 90% or lower than 10%.
- 20% decline in battery capacity is assumed during the lifetime.
- 4k swings @ 100% DoD and 500k @ 6% DoD, (Energy optimized battery).
- 3-4 hours between battery charging.
- Auxiliary power control and brake pad wear is excluded from the analysis.
- The yearly travelled distance is 60 000 km.
- The markup factor is 1.5.
- Fuel reduction due to avoiding engine idling at night stops is not regarded.
- Yearly engine efficiency improvement is 1 percentage point.
- Fuel price, battery price and battery mass is changed by year.

10. Results year 2020

These results are relevant for a truck purchased year 2020. The assumptions regarding, e.g. fuel price, are for year 2022. The reason is that the average ownership cost for the first five years is of interest. Only the variants with feasible performance are analyzed.

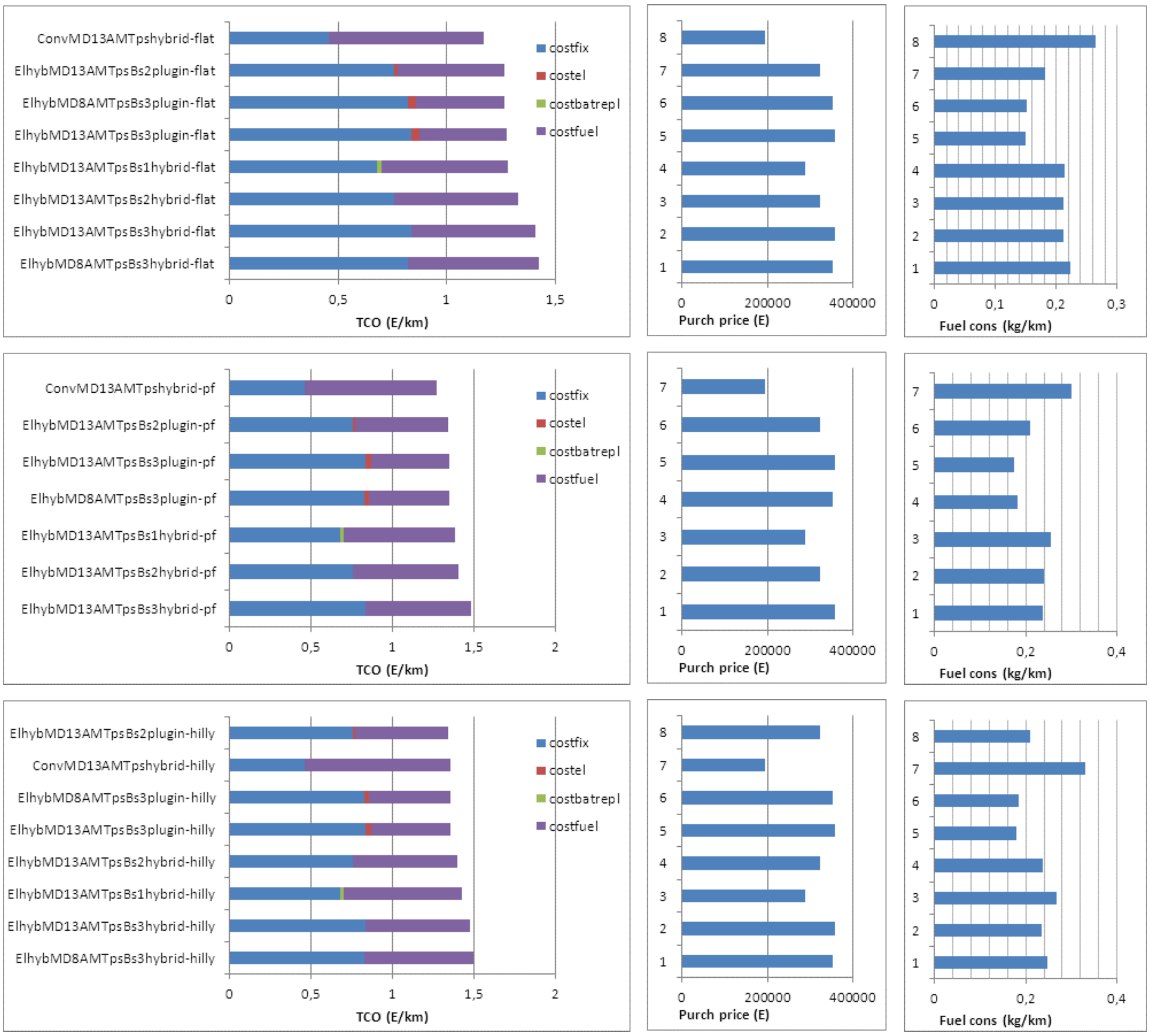


Figure 6. *Hybrid. Flat (top), pf (middle) and hilly (low).*

11. Results year 2025

These results are relevant for a truck purchased year 2025.

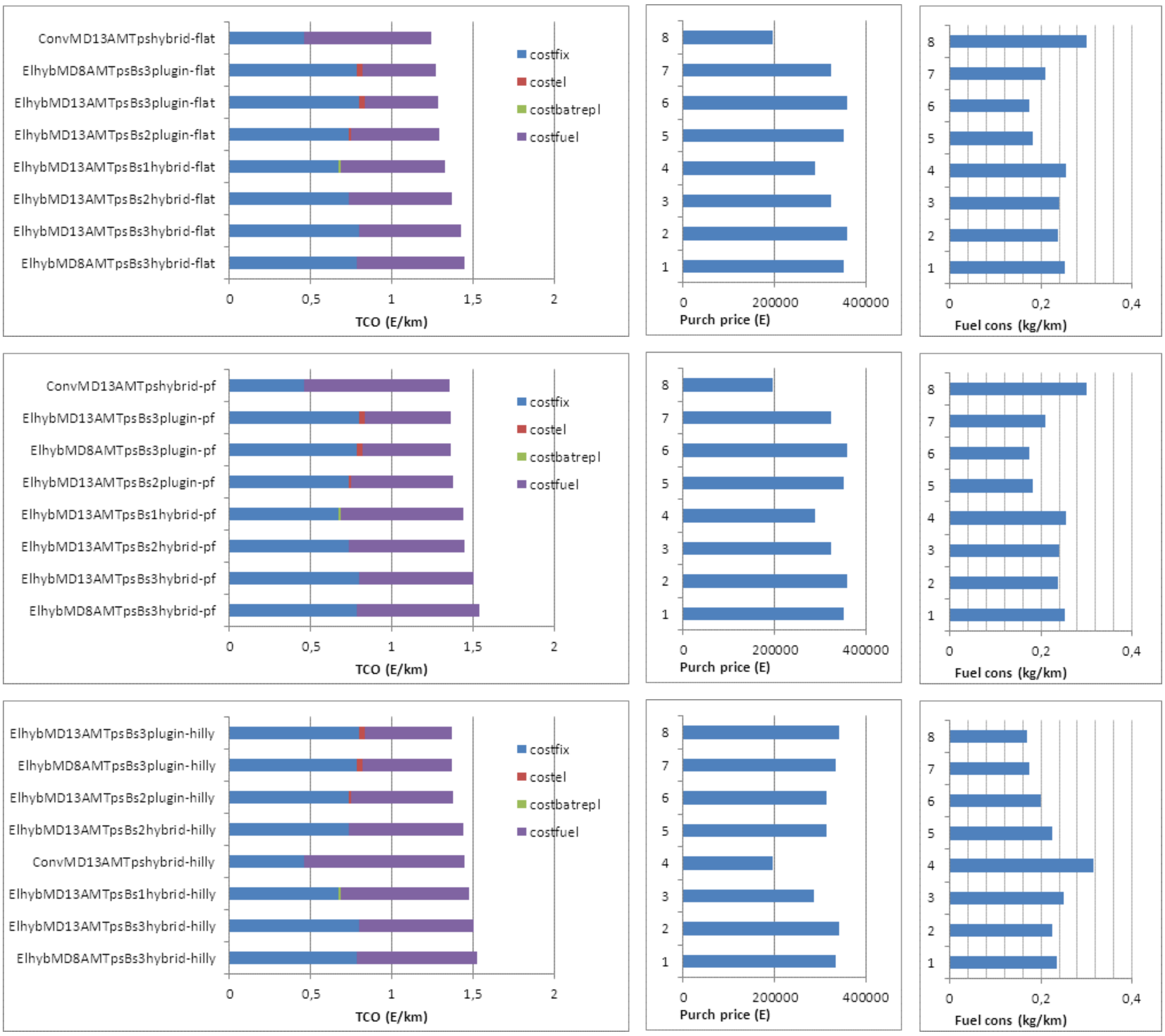


Figure 7. *Hybrid. Flat (top), pf (middle) and hilly (low).*

12. Results year 2030

These results are relevant for a truck purchased year 2030.

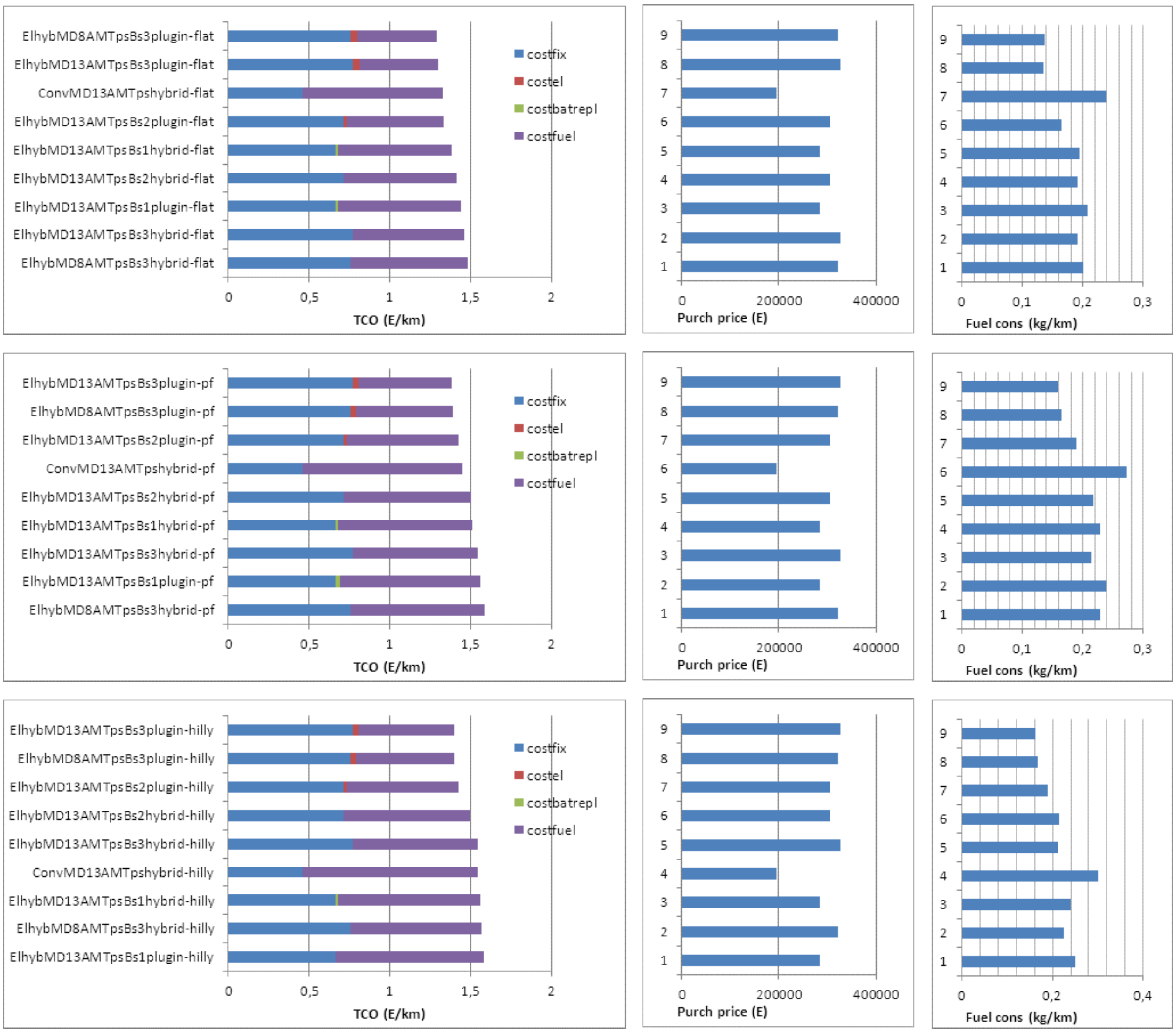


Figure 8. *Hybrid. Flat (top), pf (middle) and hilly (low).*

13. Changes for revised results

During the project results in Chapter 10-12 were presented outside the project. Some "mistakes" in the data setting where identified, hence the analysis is updated with revised changes in the data setting. Following major changes are utilized:

- New masses for the different variants have been updated, see 'massref revised results' in chapter "Mass setting of different powertrain variants in [1].
- Less variants are considered for the revised results, see variants in Table 10.
- For the plugin hybrids, charging is only performed overnight.
- The jackknife stability aspect is considered. It is further described in [8].
- Yearly driving distance is changed from 60,000 km to 150,000 km.
- Production cost for add on systems in electrified vehicles, e.g. cables, electric AC is changed from 50,000 Euro to 5,000 Euro.
- Assumed fuel (diesel) price 2015 changed from 1.70 to 1.28 Euro/liter (value adding tax is excluded).
- Assumed price of electricity 2015 changed from 0.065 Euro/kWh to 0.1 Euro/kWh.
- Over speeding means that a truck in the end of a hill increases the speed by converting potential energy to kinetic. From this fuel is saved. Fuel consumption reduction is set to 6 % for conventional vehicles due to over speed compensation [1]. For the hybrids over speed is assumed to not affect the fuel consumption.
- Chassis cost reduced from 110,000 Euro to 73,700 Euro.
- Interest rate increased from 5% to 10%.

Table 10. Simulated variants in revised results.

ConvMD13AMTps
ElhybMD13AMTpsBs1
ElhybMD13AMTpsBs2
ElhybMD13AMTpsBs3

14. Data setting for revised results

Fuel price setting is especially critical and debatable, hence the setting is here motivated. The 2015 EU fuel price is 1.70 Euro/liter. It is based on average of France, Germany, Italy and Sweden for 2013 and projected to 2015. Fuel prices year 2013 are from [4].

Assuming a value added tax of 25%; the price relevant for a truck owner year 2015 is 1.28 Euro/liter. The yearly fuel price increase for base evolution scenario is 3% per year, see average forecast in Figure 9. The high increase scenario is 5% per year and the low is 0%, also motivated from Figure 9.

An alternative fuel prediction study is from IMF [6]. It predicts an increase in 10 years of 80%, see Figure 9, much higher compared to the 10 year prediction in Figure 9 that is "only" 30%. The results in this study are based on the more conservative Volvo prediction.

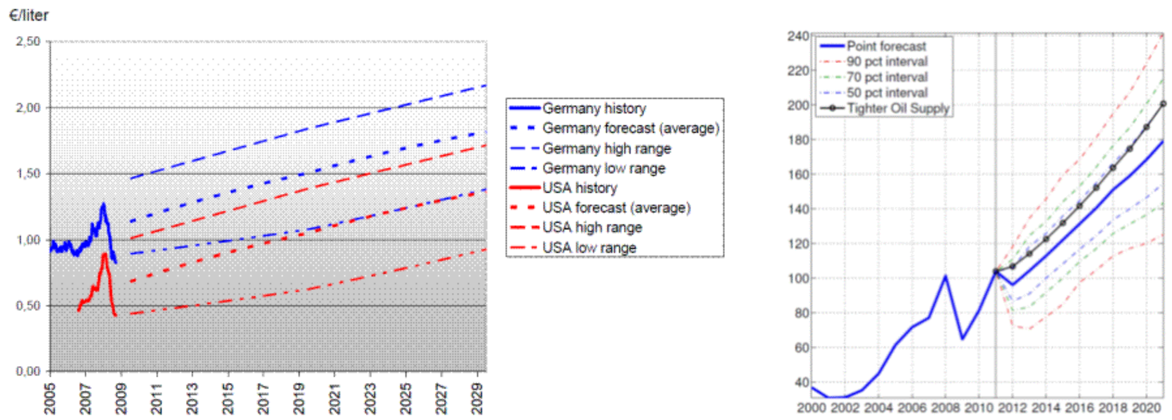


Figure 9. *Volvo estimated fuel price increase [5] (left) and IMF[6] (right). According to [4], is German diesel price Feb 2013 1.4 liter/Euro. Well in line with the Volvo prediction from 2009.*

The electricity price is 0.1 Euro/kWh, it is the recommended 2015 price setting in the Columbus project. Another reference is [7], the electricity price 2013 in the cheapest European country 0.07 Euro/kWh and in the most expensive it is 0.17 Euro/kWh.

The data setting of the evaluated battery sizes are presented in [1]. The power capacity is similar to the power capacity of the electric machine (EXAM). Details for the extensive analyses performed to achieve this is presented in [1].

Table 11. Battery data [1].

Property	**Size index 1**	**Size index 2**	**Size index 3**	**Comment**
Cell type	A123MUltra	SaftVL45E	SaftVL45E	A123MUltra is power optimized while SaftVL45E is energy optimized.
Energy capacity (kWh)	6	52	91,4	Approximate
Charge power capacity (kW)	119	96	169	Very approximate
Discharge power capacity (kW)	474	192	338	Very approximate
Total cell mass year 2015 (kg)	167	524	918	
Total pack mass year 2025 (kg)	167	524	918	5% cell mass decrease per year 2015-2025 gives 60% of 2015 mass. The cell mass is assumed to constitute 60% of the total pack mass.
Production cost (kEuro)	10.6 (2015) 6,5 (2025)	48 (2015) 28,5 (2025)	84 (2015) 50 (2025)	5% price decrease per year 2015-2025 gives 60% of 2015 price.

Other data setting used for the analysis in this document is defined in [1] and [2].

15. Results for revised results 2025

Figure 10-Figure 13 show TCO, Fuel consumption, Payback time and Purchase price for conventional, winning hybrid and plugin variants for the following task types; Flat, Pre-flat, Hilly and LH01. Results only consider a truck purchased year 2025. The battery sizes (Bs1, ..) are defined in Chapter 14.

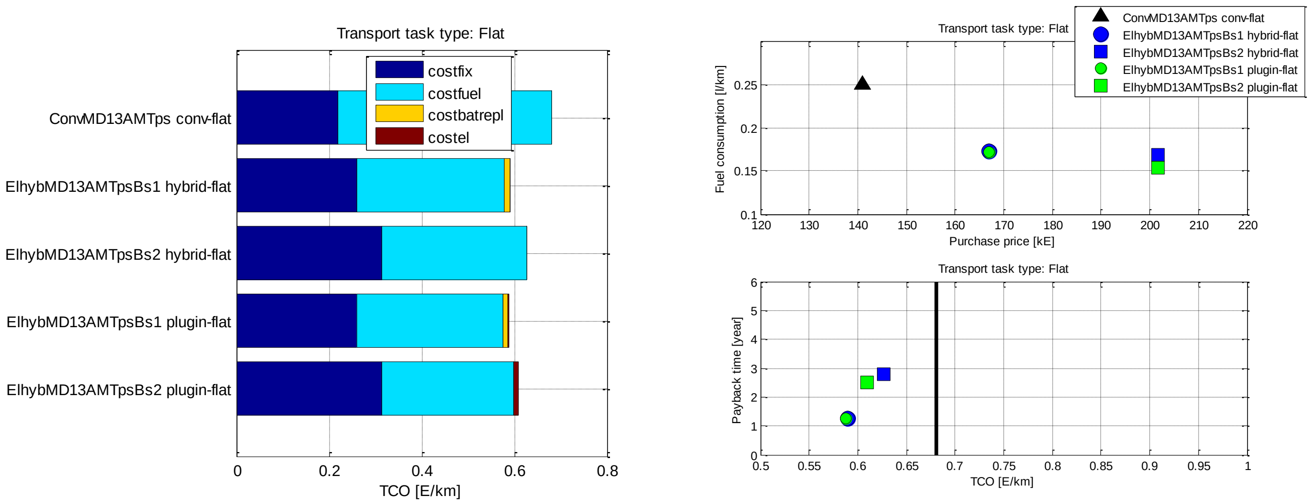


Figure 10. *TCO results for conventional and hybrid and plugin-variants for two battery sizes. Results are for task type Flat. For the small battery (Bs1) the battery is replaced one time during economic lifetime, no replacements during economic lifetime for the bigger battery (Bs2).*

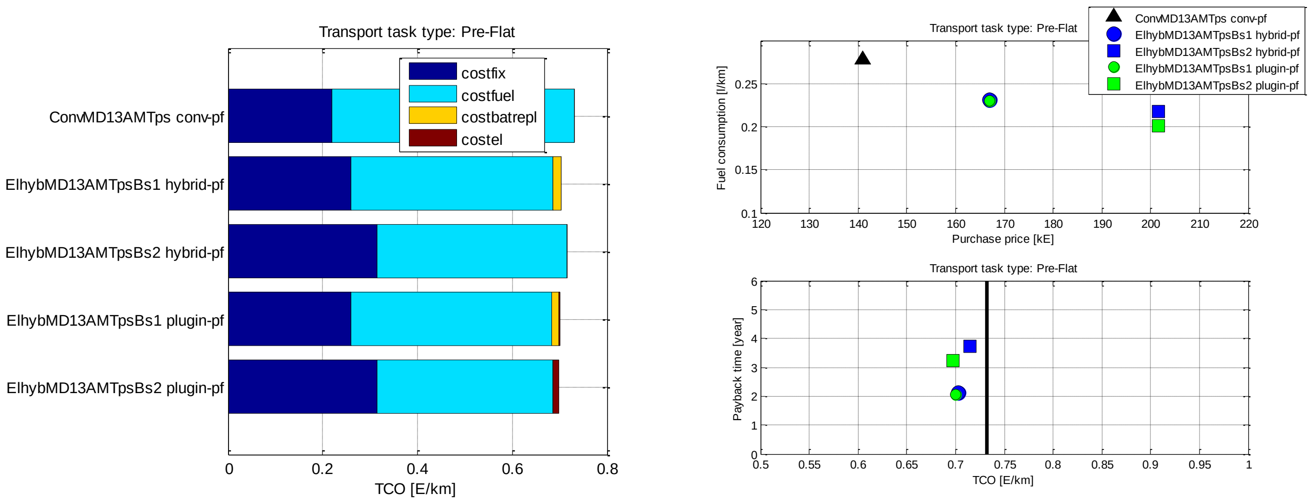


Figure 11. *TCO results for conventional (black), winning hybrid (blue) and plugin (green). Results are for task type Pre-Flat. For the small battery (Bs1) the battery is replaced one time during economic lifetime, no replacements during economic lifetime for the bigger battery (Bs2).*

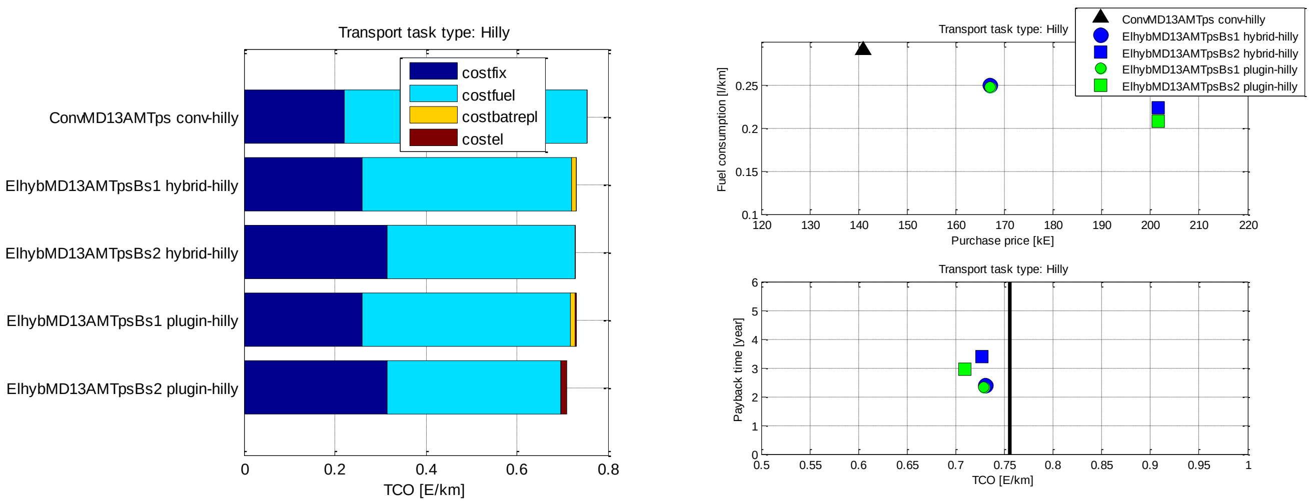


Figure 12. *TCO results for conventional (black), winning hybrid (blue) and plugin (green). Results are for task type Hilly. For the small battery (Bs1) the battery is replaced one time during economic lifetime, no replacements during economic lifetime for the bigger battery (Bs2).*

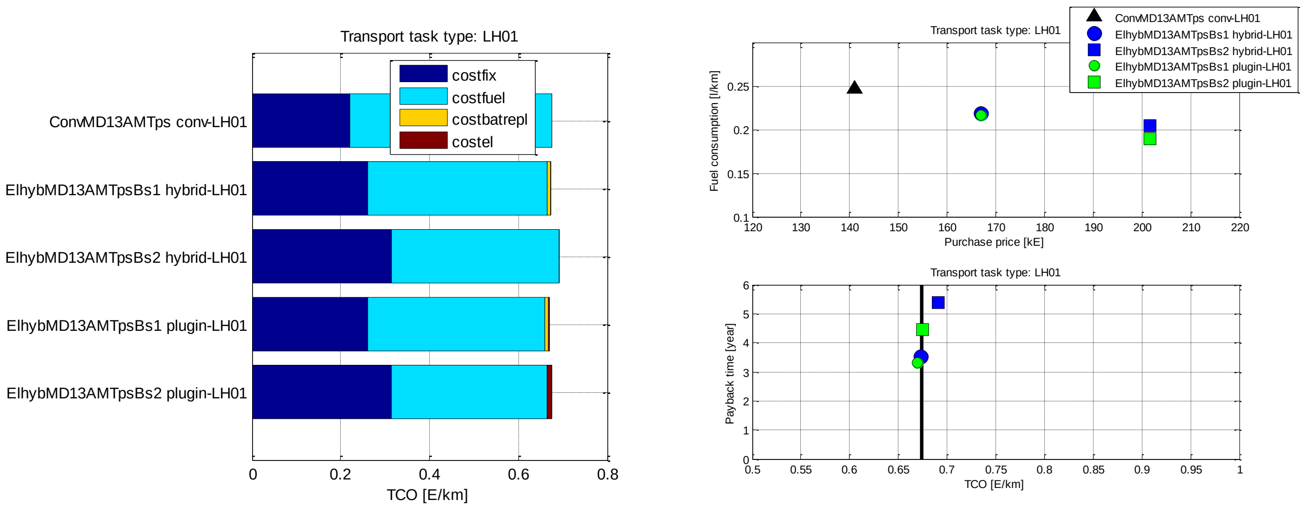


Figure 13. *TCO results for conventional (black), winning hybrid (blue) and plugin (green). Results are for task type LH01. For the small battery (Bs1) the battery is replaced one time during economic lifetime, no replacements during economic lifetime for the bigger battery (Bs2).*

Figure 14 shows the relative fuel consumption distribution for the hybrid and plugin variants with the lowest TCO, one plot for each task type. See equation (20) how the relative fuel consumption is calculated. As can be seen in the figure, the relative fuel consumption varies quite a lot between the individual driving cycles in each transport task group. One extreme example is for the first plot, for transport task type Flat where one driving cycle results in a fuel reduction of almost 50%, see Appendix 28 for more information regarding this result.

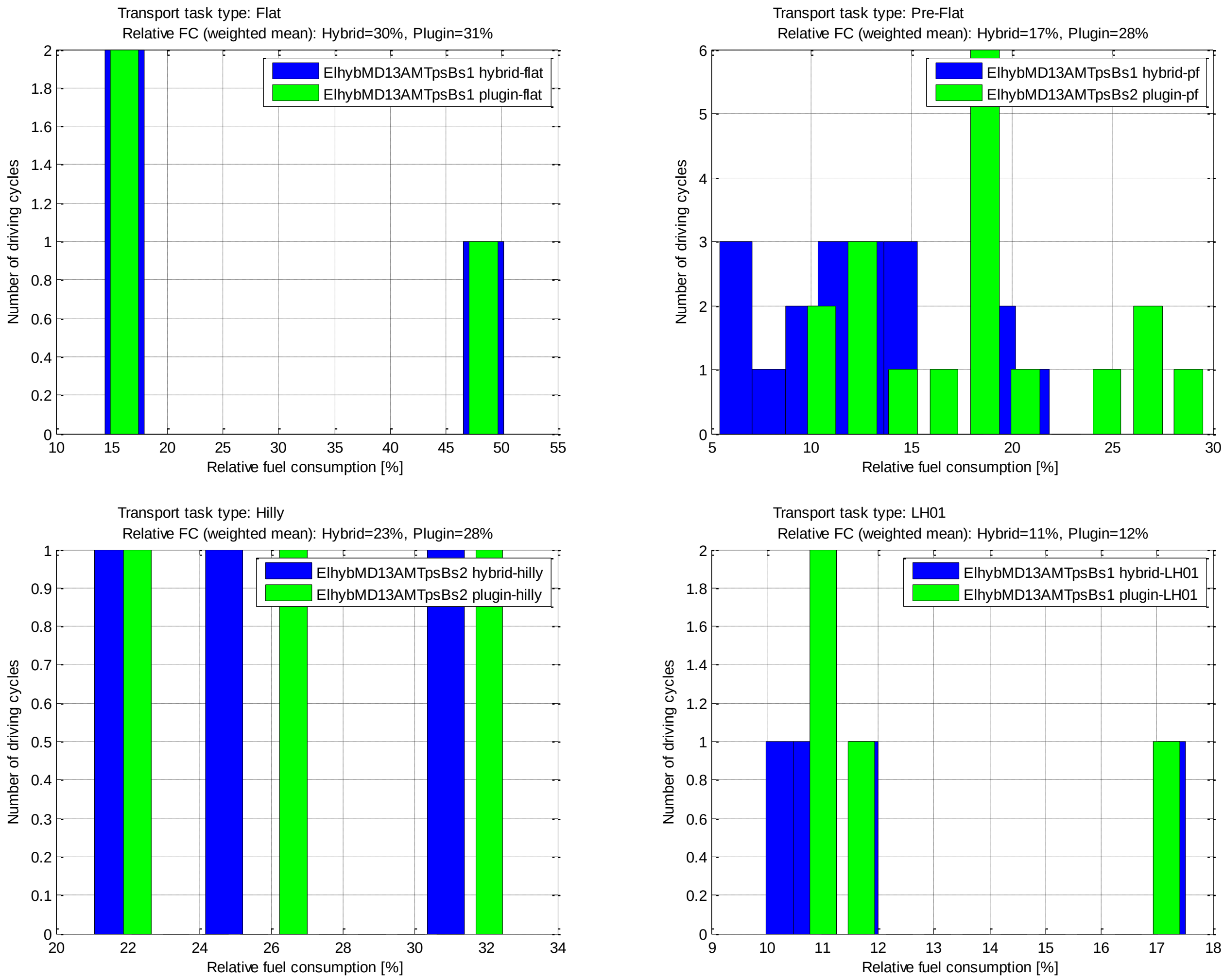


Figure 14. *Relative fuel consumption reduction for winning hybrid and plugin variants. One plot for each transport task type; Flat, Pre-Flat, Hilly and LH01.*

16. Sensitivity analysis

This chapter presents the results of an analysis studying how the change in fuel and battery price affects the cost efficiency of hybrid long haul trucks. 11 different scenarios are evaluated, see Table 12. Interest rate and yearly mileage are potential additional parameters of interest.

Table 12. Scenarios.

Scenario	Description	Setting
base	The base setting	The setting is equal to the evaluation presented in Chapter 13-15.
expensivefuel	High predicted fuel price.	Price increase, i.e. 5% increase per year and year. Motivated in Chapter 14.
cheapfuel	Low predicted fuel price.	No price increase, i.e. 0% increase per year and year. Motivated in Chapter 14.
expensivebatt	High predicted battery price.	No price decrease, i.e. 0% decrease per kWh and year.
cheapbatt	Low predicted battery price.	High price decrease, i.e. 10% decrease per kWh and year.
expensivehybaddon	High product cost for non-powertrain subsystems (for example electric AC) in electrified vehicles.	Set to 20 k Euro, Originally set to 5 k Euro.
expensiveelectricity	High predicted electricity price.	High price decrease, i.e. 3% decrease per kWh and year. This increase is an author estimation.
cheapelectricity	Low predicted electricity price.	Low price decrease, i.e. 1% decrease per kWh and year. This increase is an author estimation.
cheapfuelexpbattery	The fuel price is low and battery price is high. Bad scenario for hybrids	Combination of cheapfuel and expensivebatt scenarios.
expfuelcheapbattery	The fuel price is high and battery price is low. Good scenario for hybrids	Combination of expensivefuel and cheapbatt scenarios.
loweredbattlifetime	The number of allowed cycles as function of DoD is lowered, representing a lowering in the battery cycling lifetime.	The number of cycles for different DoDs are lowered by a factor of 4. The change is described by Table 13.

Table 13. Lowering the number of allowed battery cycles for the SAFT battery.

DoD (%)	1	6	12	25	50	100
Original Ncycles	1000k	500k	140k	31k	12k	4k
Lowered Ncycles	250k	125k	35k	7.8k	3k	1k

The measure studied is the relative TCO difference between the conventional powertrain and the most cost efficient hybrid and plugin hybrid powertrains. The measure δ defined in (20) is positive when an electrified powertrain is favorable, i.e. have a lower TCO compared to conventional powertrains.

$$\delta = \frac{TCO_{\mathrm{conv}} - TCO_{\mathrm{hybrid}}}{TCO_{\mathrm{conv}}} \tag{20}$$

Figure 15-Figure 17 show schematically how δ can vary with year and scenario[1]. It shall be stressed that δ is most reliable for the base scenario because the analysis in Chapter 10-Chapter 12 are adapted for this scenario. Table 14 shows the fuel, battery and electricity prices for each year in Figure 15-Figure 17, according to the scenarios in Table 12.

Figure 15-Figure 16 show the sensitivity analysis for the hybrid and plugin variants on the Pre-flat transport tasks using the A123 battery. Since only a little grid electricity is utilized for the plugin variant with the A123 battery the results for the hybrid and plugin variants are very similar. Therefore, also the change in electricity price has no effect for the plugin, the lines for cheap and expensive electricity prices are positioned on the base line.
Figure 17 shows the sensitivity analysis for the plugin variant on the Pre-flat transport tasks using the SAFT battery. For this variant the outcome of the battery price affects the result heavily since this variant uses the bigger and more expensive SAFT battery. Also for this variant, the outcome of the electricity price plays a little roll for the TCO in the future.

[1] From a hybrid powertrain perspective, δ shall be regarded as a bit pessimistic, for the non-base scenarios. The reason is that the operational costs in the TCO evaluation not is based for the price settings for these scenarios.

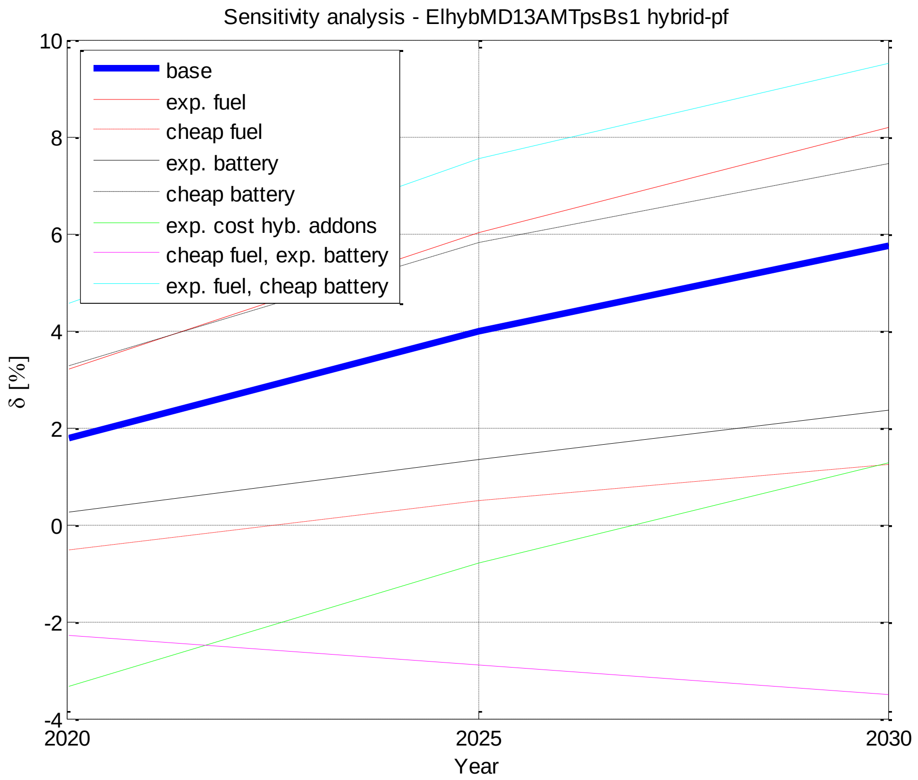


Figure 15. *Schematic plot of desired results for hybrid variant using the small battery (A123) on the Pre-flat transport tasks.*

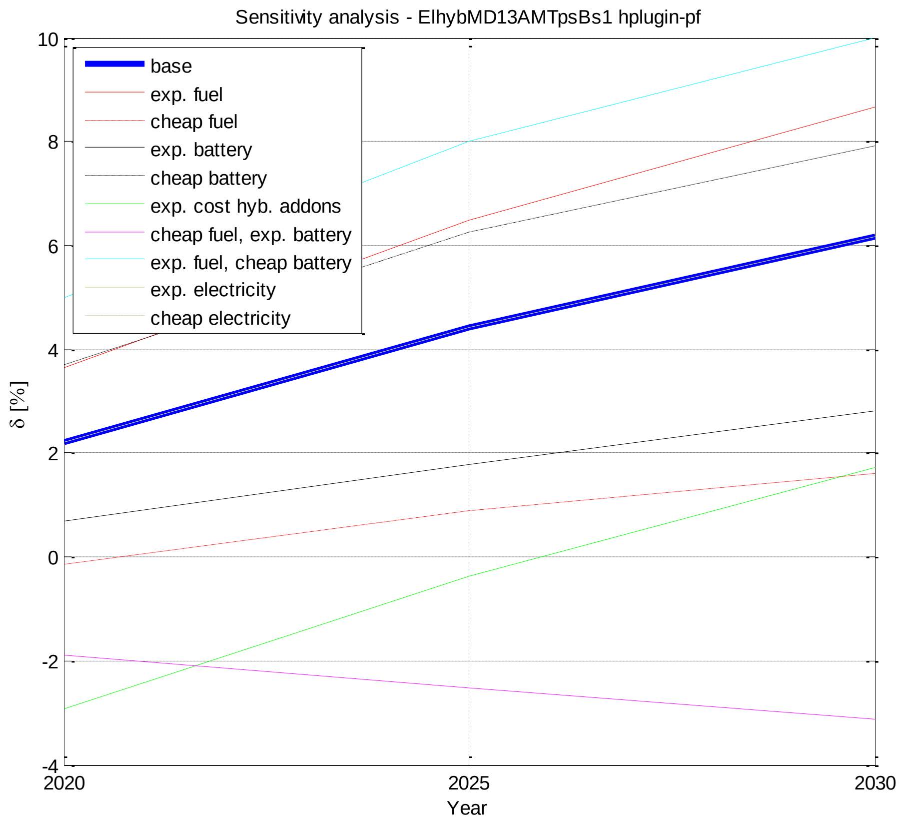


Figure 16. *Schematic plot of desired results for plugin variant, using the small battery (A123) on the Pre-flat transport tasks. The lines for expensive and cheap electricity lie on top of the base line due to that only at little electricity is utilized for the plugin variant and the electricity price has a minor affect.*

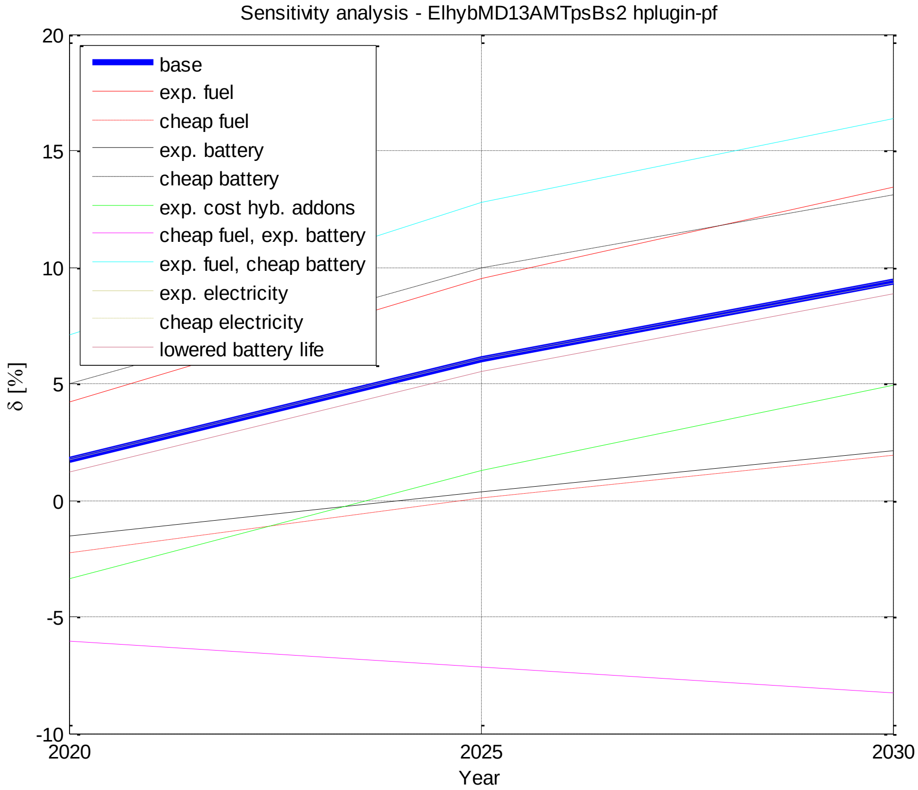


Figure 17. *Schematic plot of desired results for plugin variant using the middle battery (Small SAFT) on the Pre-flat transport tasks. The lines for expensive and cheap electricity lie on top of the base line due to that only at little electricity is utilized for the plugin variant and the electricity price outcome does not affect the results much.*

Table 14. Fuel, el and battery prices for the different scenarios in Table 12.

Scenario	**2020**	**2025**	**2030**	**Unit**
basefuel	1.48	1.721	1.99	[Euro/l]
baseel	0.112	0.124	0.139	[Euro/kWh]
basebattery	Bs1: 8.4 Bs2: 36.8	Bs1: 6.5 Bs2: 28.5	Bs1: 5.0 Bs2: 22.1	[kEuro]
expensivefuel	1.63	2.09	2.66	[Euro/l]
cheapfuel	1.28	1.28	1.28	[Euro/l]
expensivebatt	Bs1: 10.6 Bs2: 46.4	Bs1: 10.6 Bs2: 46.4	Bs1: 10.6 Bs2: 46.4	[kEuro]
cheapbatt	Bs1: 6.25 Bs2: 27.4	Bs1: 3.69 Bs2: 16.2	Bs1: 2.18 Bs2: 9.55	[kEuro]
expensiveelectricity	0.116	0.134	0.156	[Euro/kWh]
cheapelectricity	0.105	0.111	0.116	[Euro/kWh]

17. Conclusions

Chapter 9-12 presents the results from a first evaluation. In Chapter 13-16 some "non-correct" data setting have been revised. Conclusions are primary made from the revised analysis, i.e. Chapter 13-16, because it utilizes more correct prerequisites. Some conclusions are:

- By utilizing sophisticated predictive energy management, significant fuel consumption reduction, 10-30% depending on transport task, is possible for Volvo FH hybrid trucks. The major explanation is that a long prediction horizon enables extensive regeneration of potential energy. The energy management control can prepare the battery energy level for coming down and uphill situations in such a way that energy wasting, for example engine braking, is minimized.
- The TCO is probably, after 2020, better for hybrid Volvo FH trucks compared to conventional Volvo FH truck. This is valid for most European countries. The difference is up to 15% for a FH truck bought after 2030. This indicates that a paradigm shift in propulsion of long haul trucks could start up after ~2020.
- The purchase price of a strong hybrid Volvo FH is 30-60 kEuro higher compared to the conventional trucks.
- The TCO of the plugin hybrid is lower compared to the hybrid. The explanation is that reduction in fuel consumption cost, due to grid energy, is higher than the added electricity and battery degradation cost.
- An appropriate battery energy capacity is 5-50 kWh. The indication is that an energy optimized LiIon battery is suitable. Further studies are needed to identify a more exact value and cell type.
- Fuel price and battery cost (Euro/kWh) are two very important parameters for the cost efficiency of strong hybrid Volvo FH trucks. Electricity price has a minor influence.
- For scenarios with no fuel price increase from 2015, i.e. always 1.28 Euro/liter, and battery prices unchanged from 2015, hybrid Volvo FH trucks will have a TCO higher compared to conventional Volvo FH trucks.
- The yearly mileage has a major influence on the cost efficiency of electrified powertrains. This setting was probably the most important update in the revised analysis part of this report. Changing the yearly mileage from 60 Mm to 150 Mm changes the hardware related part of the TCO ($cost_{\mathrm{fix}}$) from ~0.7 to ~0.2 Euro/km. A significant change favoring the hybrid and plugin variants due to their higher purchase price.
- The product cost for non-powertrain subsystems is a critical parameter, if it exceeds ~20 kEuro, it will be very challenging to achieve a competitive TCO for the hybrid vehicles. Even for future high fuel prices.

18. Potential future work

Following items are possible future undertakings:

- Evaluate other applications, coach buses are an examples.
- Study fuel saving when the predictive control in the optimization tool is limited to a near future instead of looking at the full driving cycle.
- Develop predictive control algorithms, for hybrid long haul trucks, that can be implemented on-line in a real vehicle. This is necessary for achieving similar fuel consumption reduction in real world.
- Study other energy conserving technologies, for example solar cells.
- Divide the study for different countries/regions. For example, fuel price varies highly between countries, also within for example Europe.
- Better understand the relation between hybrid vehicle TCO and transport task properties. Why are the hybrids so much more fuel efficient for some specific transport tasks?
- Extend the battery design analysis.
- Study the consequence of higher battery/EM power levels.
- Survey sources of fuel consumption reduction. How much is saved due to engine shut off, capturing of potential energy, kinetic energy regeneration.

19. Appendix - Predictive control

Predictive control is a modern and powerful control strategy which reached wide popularity in industry and process control. MPC is a form of control in which the current control action is obtained by solving on-line, at each sampling instant, a finite horizon open-loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant. Predictive control is based on the conventional optimal control that is obtained by minimization or mini-maximization of some performance criterion either for a fixed finite horizon or for an infinite horizon.

Predictive control for long haul trucks

A conceptual example is here given to increase the understanding of why predictive control is so essential for heavy long distance vehicles. Figure 18 shows a situation where the speed is constant but the altitude is decreasing between time t_A and t_B .In this time span a lot of potential energy can be captured in a vehicle with a “big enough” battery. Just 30 m in altitude change corresponds to 10 MJ in potential energy for a 35 ton truck. That is the energy content of 0.25 kg diesel.

Let us assume a rule based control strategy characterized by: 1) the target battery energy level is 50%. 2) the battery power is in relation the road slope. The control law may result in the battery energy level presented in Figure 19. The potential energy captured is only 1/3 of the battery capacity. In Figure 20 a much more effective control strategy is utilized. It prepares for the downhill by emptying the battery before the slope; it also captures power in such a way that the battery is full in the end of the slope. The result is that approximately three times more energy is regenerated in the case of predictive control.

The consequence, in this simple example, is that the more sophisticated predictive control will give a much lower fuel consumption compared to the simpler rule based control. The important reflection from this is that a predictive control is needed to really take advantage of the hybrid hardware in heavy long distance vehicles.

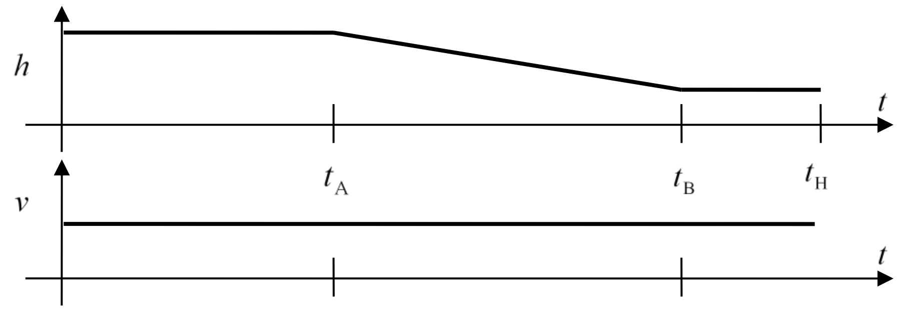


Figure 18. *Speed and terrain prediction.*

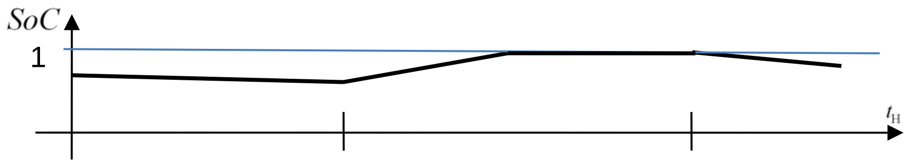


Figure 19. *Non predictive SoC control. SoC is the battery energy level.*

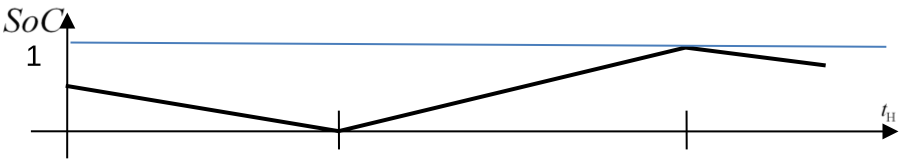


Figure 20. *Predictive SoC control.*

Figure 21 shows how a predictive controller gives and derives information from the environment and the vehicle. Realizing this kind of controller online in a real vehicle is a challenge.

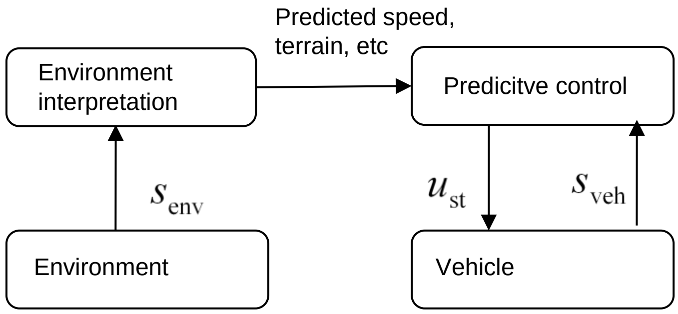


Figure 21. *System overview.* s_{env} *is raw data from the environment. It is processed before fed into the predictive controller. The control command* s_{env} *can for example include engine torque. The controller needs vehicle states* s_{veh} *such as energy battery level.*

20. Appendix – TCO and fuel consumption for all variants 2025 (from Revised results)

In Chapter 15 (Revised results) only TCO results for the winning variants were presented. Figure 22 shows TCO results for all variants of the four different transport task types.

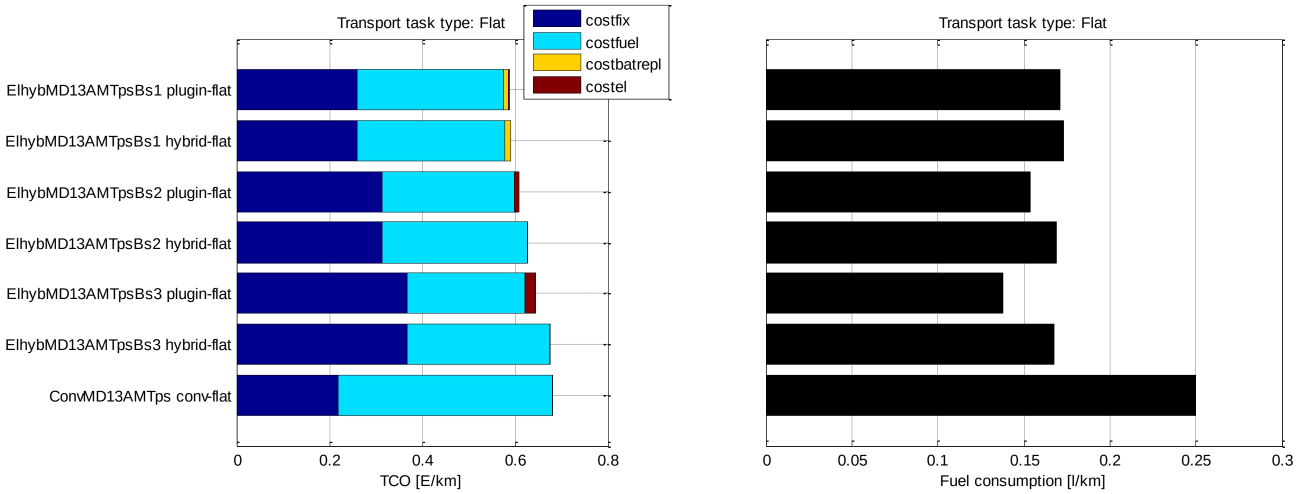


Figure 22. *TCO [E/km] and fuel consumption [l/km] for all variants for the Flat transport task type.*

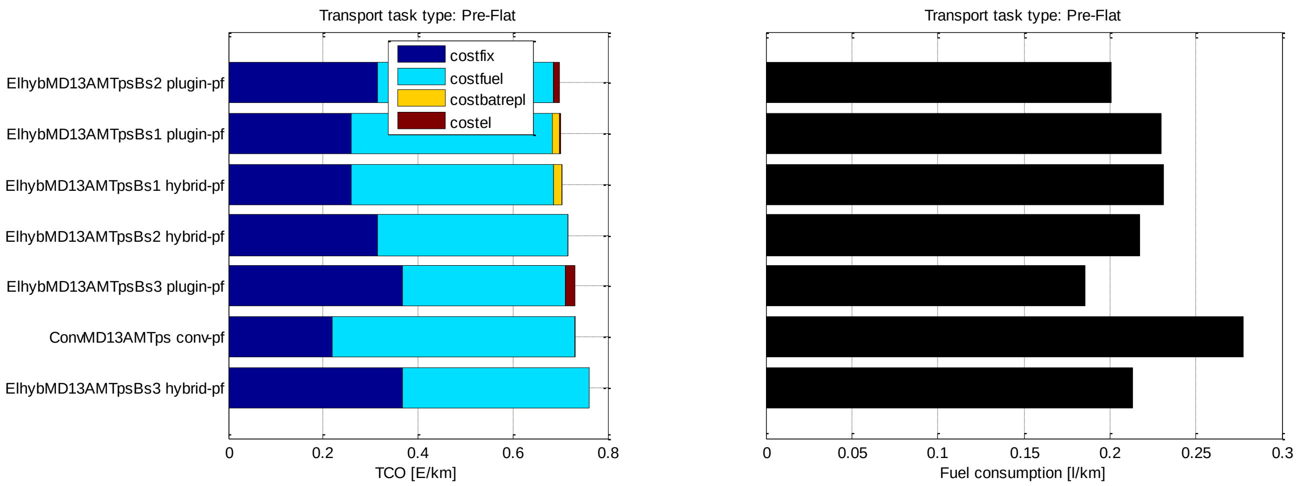


Figure 23. *TCO [E/km] and fuel consumption [l/km] for all variants for the Pre-Flat transport task type.*

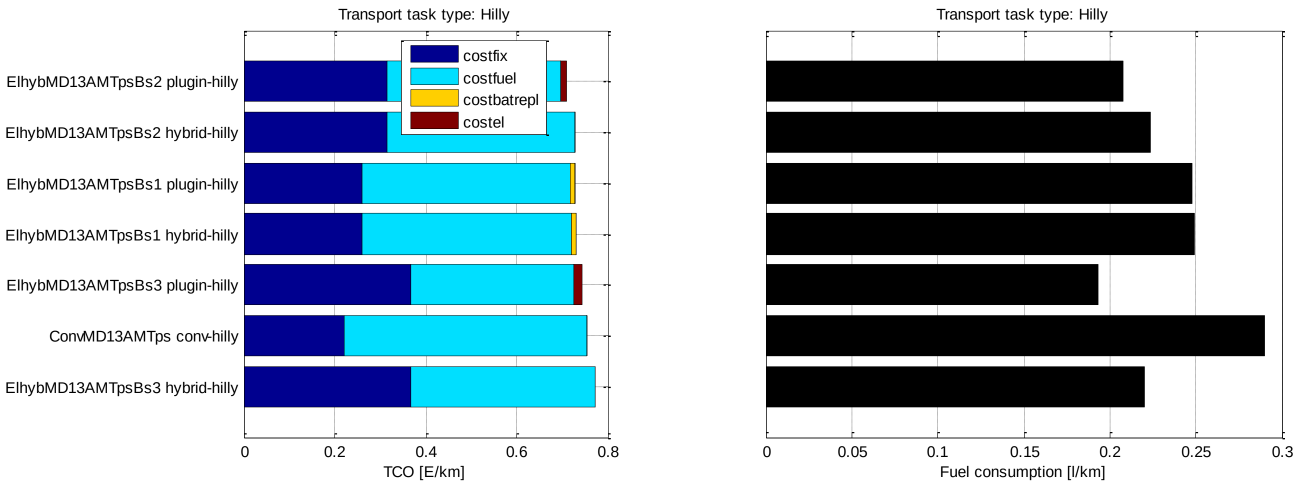


Figure 24. *TCO [E/km] and fuel consumption [l/km] for all variants for the Hilly transport task type.*

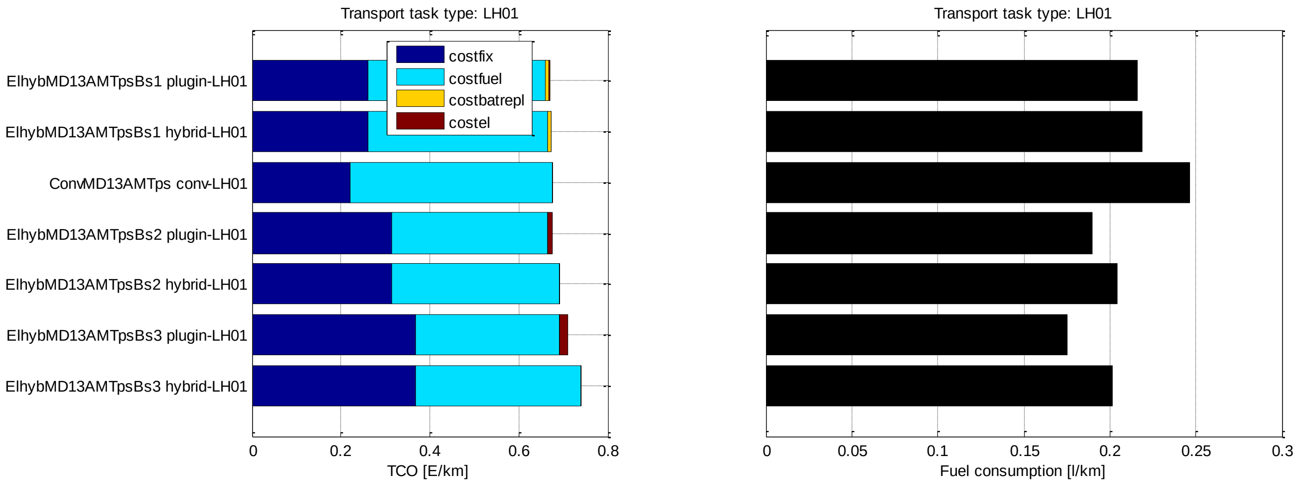


Figure 25. *TCO [E/km] and fuel consumption [l/km] for all variants for the LH01 transport task type.*

21. Appendix – Simulations results of all variants 2025 (from Revised results)

Provided in Table 15 are simulation results presented for all variants included in the Revised results. All cost values are defined in [Euro/km], fuel consumption (dmfuel) is defined in [liter/km], purchase price is defined in Euro. ‘costfix’ includes cost for one battery, ‘costbatrepl’ includes only extra costs for replaced batteries.

Table 15. Simulation results for all variants on all task types.

Pwtname	Task type	Purch price	massref	costfix	costfuel	costel	costbatrepl	costtot	dmfuel
ConvMD13AMTps	conv-flat	141000	40000	0,220	0,461	0,0000	0,000	0,681	0,250
ConvMD13AMTps	conv-pf	141000	40000	0,220	0,512	0,0000	0,000	0,732	0,278
ConvMD13AMTps	conv-hilly	141000	40000	0,220	0,535	0,0000	0,000	0,755	0,290
ConvMD13AMTps	conv-LH01	141000	40000	0,220	0,455	0,0000	0,000	0,674	0,246
ElhybMD13AMTpsBs1	hybrid-flat	167000	40250	0,260	0,319	0,0000	0,011	0,590	0,173
ElhybMD13AMTpsBs1	hybrid-pf	167000	40250	0,260	0,427	0,0000	0,016	0,703	0,231
ElhybMD13AMTpsBs1	hybrid-hilly	167000	40250	0,260	0,460	0,0000	0,010	0,730	0,249
ElhybMD13AMTpsBs1	hybrid-LH01	167000	40250	0,260	0,404	0,0000	0,009	0,673	0,219
ElhybMD13AMTpsBs1	plugin-flat	167000	40250	0,260	0,316	0,0011	0,011	0,588	0,171
ElhybMD13AMTpsBs1	plugin-pf	167000	40250	0,260	0,423	0,0011	0,016	0,701	0,230
ElhybMD13AMTpsBs1	plugin-hilly	167000	40250	0,260	0,457	0,0011	0,010	0,729	0,248
ElhybMD13AMTpsBs1	plugin-LH01	167000	40250	0,260	0,399	0,0011	0,009	0,670	0,216
ElhybMD13AMTpsBs2	hybrid-flat	201680	40460	0,314	0,312	0,0000	0,000	0,626	0,169

ElhybMD13AMTpsBs2	hybrid-pf	201680	40460	0,314	0,401	0,0000	0,000	0,715	0,217
ElhybMD13AMTpsBs2	hybrid-hilly	201680	40460	0,314	0,413	0,0000	0,000	0,727	0,224
ElhybMD13AMTpsBs2	hybrid-LH01	201680	40460	0,314	0,377	0,0000	0,000	0,691	0,204
ElhybMD13AMTpsBs2	plugin-flat	201680	40460	0,314	0,284	0,0117	0,000	0,610	0,154
ElhybMD13AMTpsBs2	plugin-pf	201680	40460	0,314	0,371	0,0122	0,000	0,697	0,201
ElhybMD13AMTpsBs2	plugin-hilly	201680	40460	0,314	0,383	0,0119	0,000	0,709	0,208
ElhybMD13AMTpsBs2	plugin-LH01	201680	40460	0,314	0,350	0,0112	0,000	0,675	0,190
ElhybMD13AMTpsBs3	hybrid-flat	235850	40700	0,367	0,309	0,0000	0,000	0,677	0,168
ElhybMD13AMTpsBs3	hybrid-pf	235850	40700	0,367	0,394	0,0000	0,000	0,761	0,213
ElhybMD13AMTpsBs3	hybrid-hilly	235850	40700	0,367	0,406	0,0000	0,000	0,774	0,220
ElhybMD13AMTpsBs3	hybrid-LH01	235850	40700	0,367	0,372	0,0000	0,000	0,739	0,202
ElhybMD13AMTpsBs3	plugin-flat	235850	40700	0,367	0,254	0,0230	0,000	0,645	0,138
ElhybMD13AMTpsBs3	plugin-pf	235850	40700	0,367	0,343	0,0209	0,000	0,731	0,186
ElhybMD13AMTpsBs3	plugin-hilly	235850	40700	0,367	0,357	0,0204	0,000	0,745	0,193
ElhybMD13AMTpsBs3	plugin-LH01	235850	40700	0,367	0,324	0,0199	0,000	0,711	0,175

22. Appendix – Reference values of fuel consumption of conventional Volvo FH truck

Table 16. Fuel consumption of conventional 31.5 ton Volvo FH truck,

Reference	Transport task	Fuel cons – reference (liter/km)	Fuel cons – study in this report (liter/km)	Comment
Simulation of Fuel-saving Potential of Light-weight Vehicles. ER-530589.	Frankfurt – Koblenz	0.31[2]	0.29	
Simulation of Fuel-saving Potential of Light-weight Vehicles. ER-530589.	Borås-Landvetter-Borås	0.27	0.26	Borås-Landvetter-Borås not present in this report but resembles TBD.
Fuel consumption tests on EuroV, 4x2T trucks, Volvo FH 500hp	Borås-Landvetter-Borås	0.31	0.26	40 ton GCW
Measurement of fuel consumption for an AMTPS and an AMTD driveline with a Eu6-MechTc engine in FP70. ER-617248. 2009.	Borås-Landvetter-Borås	0.27-0.28	0.26	Mass is 32 ton. Consumption is speed dependant.
GSP simulation by Benzaoui Hellal.	Colchester_to_ClopHill_A120	0.45	0.34	40 ton GCW
GSP simulation by Benzaoui Hellal.	Frankfurt_Koblenz	0.35	0.29	
GSP simulation by Benzaoui Hellal.	Germany	0.33	0.29	
GSP simulation by Benzaoui Hellal.	newSX256	0.31	0.27	

[2] 55 kg on 210 km.

23. Appendix – Evaluation of completely flat transport task

Transport task “d_re_sx538_Japan_amongthemountains1” is converted into a flat transport task and compared with the original one, which is a hilly transport task. This study is based on the data settings from the first evaluation, i.e. non-revised analysis which results are shown in Chapters 9-12.

Table 17 and Table 18 show results for a truck purchased in year 2020 and 2030, respectively. Figure 26 and Figure 27 show the fuel consumption for both transport tasks in 2020 and 2030, respectively.

For the hilly transport task, there is a significant reduction in fuel consumption for the Hybrid Electric Vehicles (between approx. 23% and 37% reduction respect the conventional powertrain) and the Plug-in Hybrid Electric Vehicles (between approx. 45% and 60% reduction respect the conventional powertrain). But in the case of the flat transport task, in general there is a small increase in fuel consumption (approx. 1-2% increase respect the conventional powertrain) for the Hybrid Electric Vehicles, and a significant reduction for Plug-in Hybrid Electric Vehicles (more significant for the biggest battery)

Table 17. Fuel consumption, battery replacements, and electricity cost for a hilly transport task and its flat version, year 2020.

	fc-Hilly		fc-Flat		nbat-Hilly	nbat-Flat	elcost-Hilly	elcost-Flat
Pwtname	[kg/km]	[p.u.]	[kg/km]	[p.u.]			[kWh/km]	[kWh/km]
'ConvMD13AMTps'	0.320	1.000	0.180	1.000	-	-	-	-
'HEVd13c500eu5AMTpsBat1'	0.246	0.769	0.181	1.006	1	0	0.000	0.000
'HEVd13c500eu5AMTpsBat2'	0.209	0.652	0.182	1.011	0	0	0.000	0.000
'HEVd13c500eu5AMTpsBat3'	0.203	0.634	0.184	1.021	0	0	0.000	0.000
'HEVd8k350eu6AMTpsBat3'	0.211	0.660	0.184	1.020	0	0	0.000	0.000
'HEVd5k210eu6AMTpsBat3'	0.214	0.669	0.177	0.983	0	0	0.000	0.000
'PHEVd13c500eu5AMTpsBat2'	0.175	0.548	0.140	0.774	0	0	0.288	0.350
'PHEVd13c500eu5AMTpsBat3'	0.129	0.402	0.095	0.530	0	0	0.663	0.740
'PHEVd8k350eu6AMTpsBat3'	0.129	0.403	0.088	0.487	0	0	0.681	0.740
'PHEVd5k210eu6AMTpsBat3'	0.126	0.394	0.078	0.431	0	0	0.664	0.739

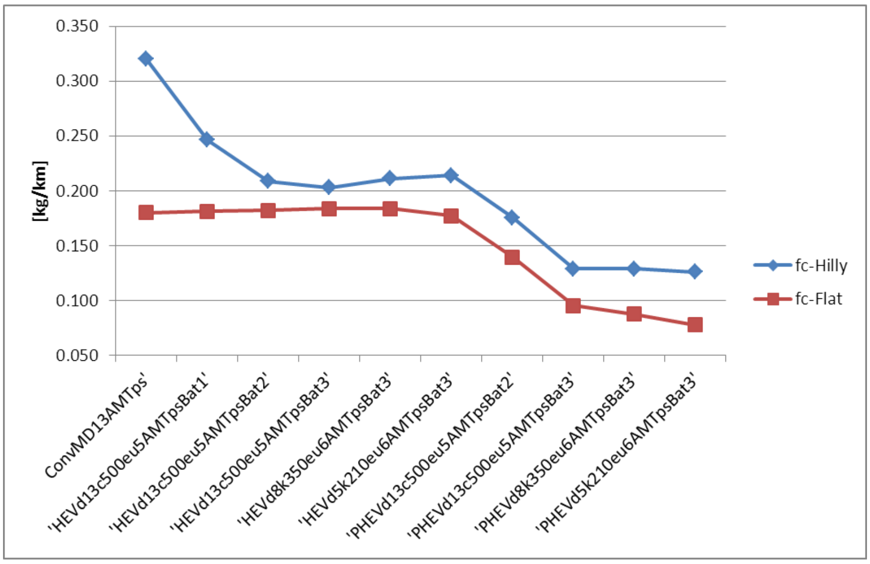


Figure 26. *Fuel consumption for a hilly transport task and its flat version for different powertrain configurations, year 2020.*

Table 18. Fuel consumption, battery replacements, and electricity cost for a hilly transport task and its flat version, year 2030.

	fc-Hilly		fc-Flat		nbat-Hilly	nbat-Flat	elcost-Hilly	elcost-Flat
Pwtname	[kg/km]	[p.u.]	[kg/km]	[p.u.]			[kWh/km]	[kWh/km]

ConvMD13AMTps'	0.290	1.000	0.163	1.000	-	-	-	-
'HEVd13c500eu5AMTpsBat1'	0.209	0.720	0.164	1.006	4	0	0.000	0.000
'HEVd13c500eu5AMTpsBat2'	0.189	0.652	0.165	1.011	0	0	0.000	0.000
'HEVd13c500eu5AMTpsBat3'	0.184	0.634	0.167	1.021	0	0	0.000	0.000
'HEVd8k350eu6AMTpsBat3'	0.191	0.660	0.166	1.020	0	0	0.000	0.000
'HEVd5k210eu6AMTpsBat3'	0.194	0.669	0.160	0.983	0	0	0.000	0.000
'PHEVd13c500eu5AMTpsBat1'	0.241	0.831	0.163	0.996	0	0	0.000	0.014
'PHEVd13c500eu5AMTpsBat2'	0.159	0.548	0.126	0.774	0	0	0.288	0.350
'PHEVd13c500eu5AMTpsBat3'	0.117	0.402	0.086	0.530	0	0	0.663	0.740
'PHEVd8k350eu6AMTpsBat3'	0.118	0.408	0.079	0.487	0	0	0.663	0.740
'PHEVd5k210eu6AMTpsBat3'	0.113	0.391	0.070	0.431	0	0	0.662	0.739

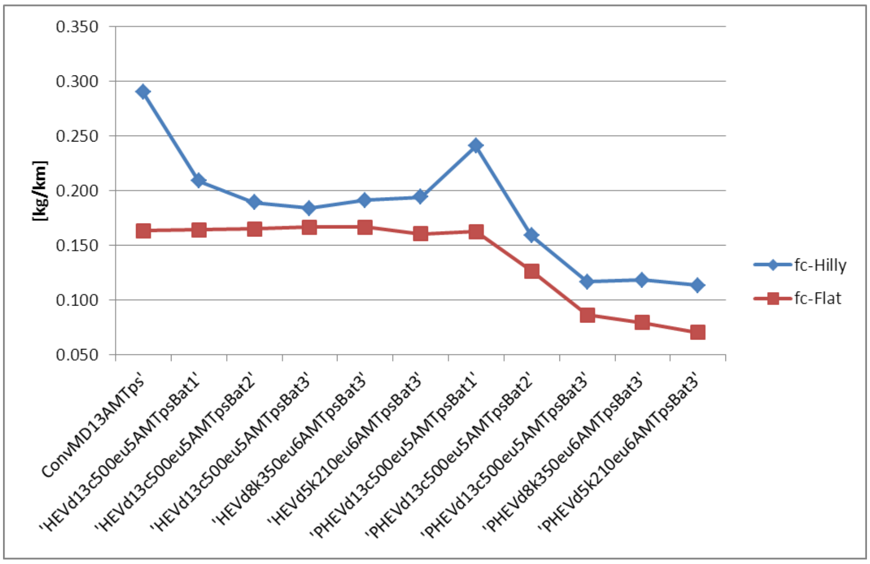


Figure 27. *Fuel consumption for a hilly transport task and its flat version for different powertrain configurations, year 2030.*

24. Appendix – Sanity check of degradation calculation by post processing of battery power

The battery state-of-charge data generated during the optimization process was used to verify the state of health of the batteries at the end of the lifetime of the study.

$$(1)\ \mathrm{n}_{\mathrm{totbat\_sanitycheck}} = \Delta SOH_{ett}(\boldsymbol{SoC}) \cdot\ ceil\left(\frac{L_{peryear}}{L_{tt}}\right) \cdot L_{ml}$$

$$(2)\ \mathrm{n}_{\mathrm{totbat\_sanitycheck}} \leq n_{totbat\_opt}$$

Table 19. Sanity check data terms.

Term	Unit	Comment	Value
ΔSOH_{ett}	(-)	Change in state-of-health after one transport task. Calculated using an improved version of function “calcdeltaSoH”.	
$\boldsymbol{SoC}$	(-)	State of Charge vector obtained from the optimization process.	
L_{ml}	(years)	Max lifetime of the study.	5
n_{totbat_opt}	(-)	Total number of batteries during the lifetime of the study (mybatt+1), obtained from the optimization process.	
$L_{peryear}$	(km/year)	The yearly travelled distance.	60000
L_{tt}	(km)	The travelled distance of the transport task.	

Table 20 and Table 21 show the results of applying Eq. (I) to the data of two transport tasks, '9553' and 'd_re_sx538_Japan_amongthemountains', respectively, in year 2025, and using the corrected data settings, i.e. the revised analysis. The second column shows the number of batteries estimated during the sanity, Eq. (I), and the third column shows the number of batteries obtained from the optimization process.

Table 20. Sanity check results, transport task '9553', year 2025.

Pwtname	$n_{totbat\_sanitycheck}$	n_{totbat_opt}
'HEVd13k500eu6AMTpsBat1'	1.2	3
'HEVd13k500eu6AMTpsBat2'	0.7	1
'HEVd13k500eu6AMTpsBat3'	0.6	1
'PHEVd13k500eu6AMTpsBat1'	1.2	3
'PHEVd13k500eu6AMTpsBat2'	0.7	1
'PHEVd13k500eu6AMTpsBat3'	0.6	1

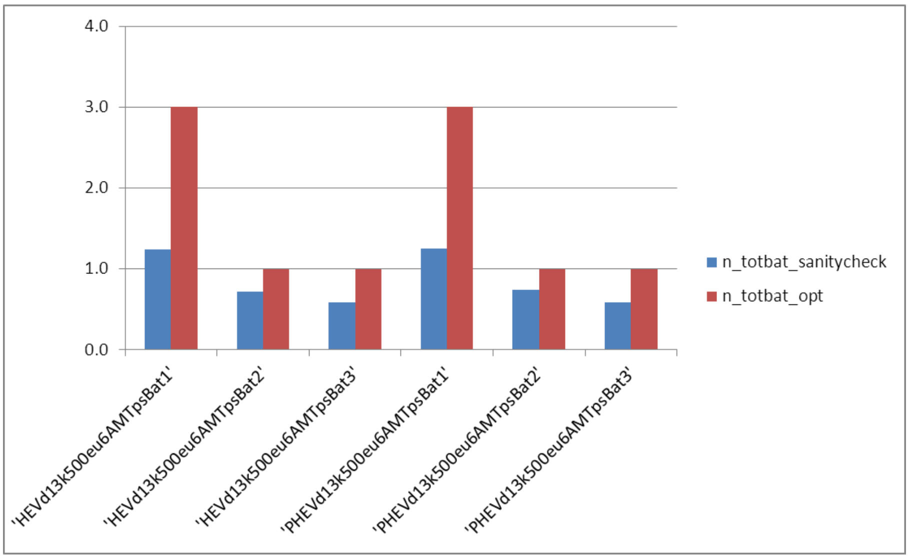


Figure 28. *Sanity check, transport task '9553', year 2025.*

Table 21. Sanity check results, transport task 'd_re_sx538_Japan_amongthemountains', year 2025.

Pwtname	$n_{totbat\_sanitycheck}$	n_{totbat_opt}
'HEVd13k500eu6AMTpsBat1'	2.1	3
'HEVd13k500eu6AMTpsBat2'	0.5	1
'HEVd13k500eu6AMTpsBat3'	0.4	1
'PHEVd13k500eu6AMTpsBat1'	2.1	3
'PHEVd13k500eu6AMTpsBat2'	0.5	1
'PHEVd13k500eu6AMTpsBat3'	0.5	1

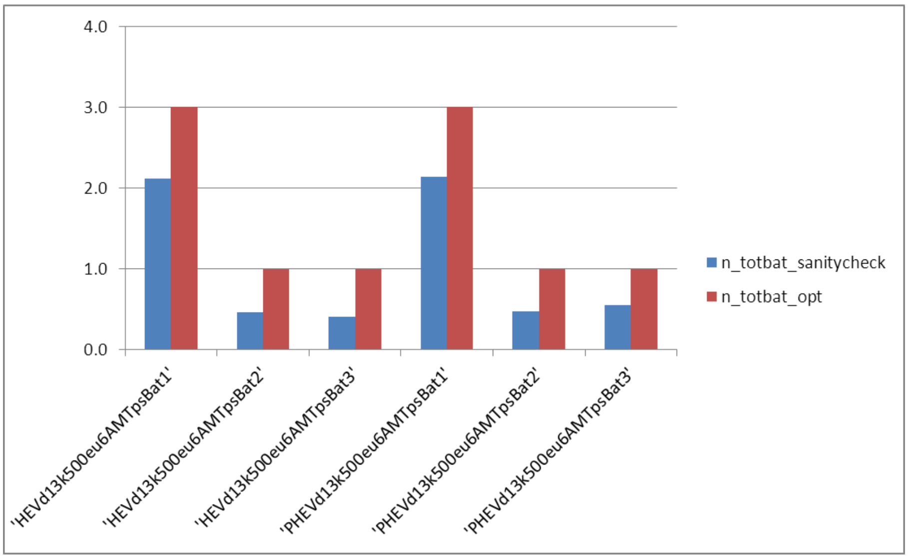


Figure 29. *Sanity check, transport task 'd_re_sx538_Japan_amongthemountains', year 2025.*

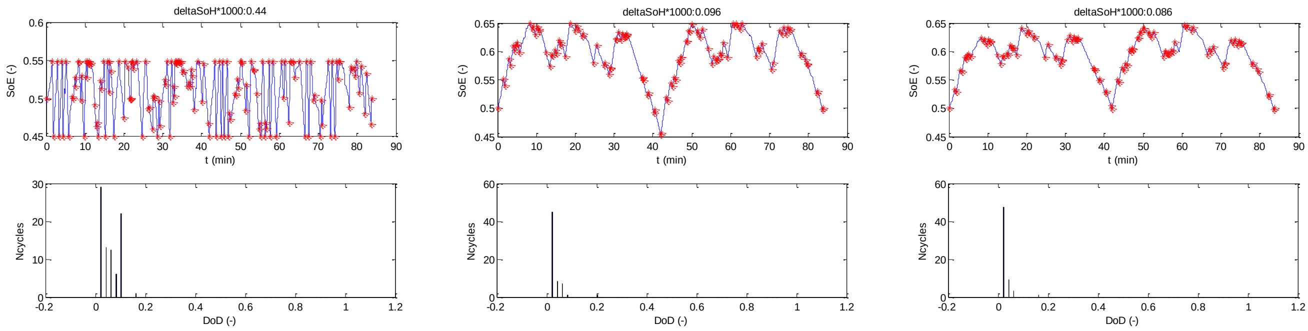


Figure 30. *ΔSOC_{ett} for transport task 'd_re_sx538_Japan_amongthemountains', year 2025. From the left to right, powertrain 'HEVd13k500eu6AMTpsBat1', 'HEVd13k500eu6AMTpsBat2', and 'HEVd13k500eu6AMTpsBat3'.*

26. Appendix - Crude method for transport task evaluation

This appendix presents a method that very roughly evaluates the potential fuel consumption reduction of a transport task utilizing hybrid technology. It also compares the rough fuel consumption evaluation with the detailed approach, earlier utilized in the report.

Basic approach

Firstly, the very basic idea is presented. In a later section Model formulation, it is generalized. In the example in Figure 31, there are three different phases. In phase 1, the traction energy E_1 must be delivered by the engine. This energy is approximately the integral of the traction power, during phase 1. In phase 2, energy $E_2$is renegerated into the buffer with the efficiency η_{ed}. Finally, in phase 3, this regenerated energy is used for propulsion. The totally energy need from the engine is expressed in (3)

$$(3)\ E_{\text{eng}} = E_1 + (E_3 - E_2 \cdot {\eta_{\text{ed}}}^2)$$

Where E_3 is the engine energy need in phase 3 if regenerated battery power would not have been available.

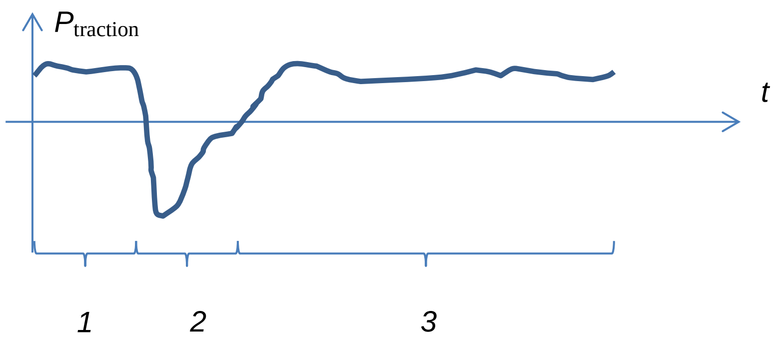


Figure 31. *Example transport task.*

Model formulation

Traction and transmission power are defined in Figure 32. Their relation is defined by (4). The max function is utilized to express that there is a restriction of regenerative power due to limitations in the electric drive.

$$(4)\ P_{\text{trans}} = \begin{cases} \max(-P_{\text{edmax}}, P_{\text{trac}} \cdot \eta_{\text{trans}}) & (P_{\text{trac}} < 0) \\ P_{\text{trac}}/\eta_{\text{trans}} & (P_{\text{trac}} > 0) \end{cases}$$

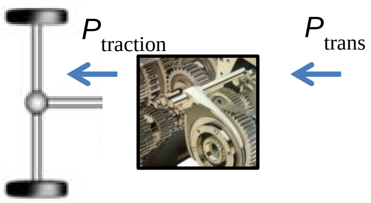


Figure 32. *Traction and transmission power.*

In (5)-(9) equations for a general formulization of the previous example. The fuel consumption (kg/km) of the conventional and hybrid powertrain, fc_{conv} and fc_{hyb}, can be regarded as outputs. The parameters are defined in Table 22.

$$(5)\ E_{\text{postrac}} = \int P_{\text{trans}}(t) \cdot (P_{\text{trans}}(t) > 0) \cdot dt$$
$$(6)\ E_{\text{negtrac}} = \int P_{\text{trans}}(t) \cdot (P_{\text{trans}}(t) < 0) \cdot dt$$
$$(7)\ L_{\text{cyc}} \cdot fc_{\text{conv}} = E_{\text{postrac}} \cdot \frac{1}{Q_{\text{fuel}} \cdot \eta_{\text{eng}} \cdot \delta_{\text{fuel}}}$$

$$(8)\ L_{\mathrm{cyc}} \cdot fc_{\mathrm{hyb}} = \quad (E_{\mathrm{postrac}} - E_{\mathrm{negtrac}} \cdot {\eta_{\mathrm{ed}}}^2) \cdot \frac{1}{Q_{\mathrm{fuel}} \cdot \eta_{\mathrm{eng}} \cdot \delta_{\mathrm{fuel}}}$$

$$(9)\ \eta_{\mathrm{ed}} = \eta_{\mathrm{em}} \cdot \eta_{\mathrm{battery}}$$

Table 22. Parameter description.

Parameter	Description
P_{edmax}	Maximum electric drive power. Restricted by either electric machine or battery power.
Q_{fuel}	Fuel heating value (J/kg)
η_{eng}	Engine efficiency (-)
δ_{fuel}	Fuel density (kg/liter)
$\eta_{\mathrm{ed}}, \eta_{\mathrm{em}}, \eta_{\mathrm{battery}}$	Electric drive, electric machine and battery efficiency.

Example analysis

The analysis in this section is approximate and only for a few driving cycles, hence the results are not valid generally. Table 23 shows the results for three different transport task (one completely flat, one predominantly flat, and one hilly) when the restriction of regenerative power is considered (P_{edmax}=120kW) or not. Pedmax means not restriction in electric drive power. Reflections:

- When no altitude change is present in the sx538 cycle, the fuel consumption reduction of the conventional truck is reduced by over 50%. This shows the enormous energy wasted when a conventional long haul truck runs the downhill.
- Regeneration of potential energy with a 120 kW electric drive reduced fuel consumption with 10-20%.
- With no restriction in electric drive power fuel consumption is reduced with 20-30%.

Table 23. Example analysis.

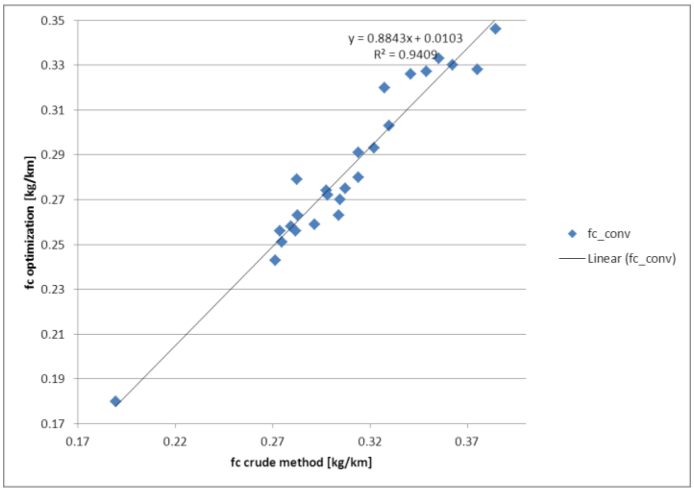
		Pedmax ON		Pedmax OFF	
Driving cycle	fc_conv [kg/km]	fc_hybrid [kg/km]	fc_reduction [%]	fc_hybrid [kg/km]	fc_reduction [%]
zeroslope_d_re_sx538_Japan_amongthemountains1	0.19	0.18	3.0	0.17	9.8
d_re_CVL_HD_National_LCG	0.28	0.26	9.1	0.23	17.7
d_re_sx538_Japan_amongthemountains1	0.33	0.26	19.0	0.23	29.5

Comparative analysis

The following table shows the results when the crude method is applied to all the transport tasks considered in the analysis. For a sake of comparison, the fuel consumption for the conventional powertrain (for a truck purchased year 2020) and obtained with the optimization algorithm (3rd column), is included, as well as the fuel consumption reported in the euroFOT cycles with the corresponding weight of the truck.

Driving cycle	Fuel consumption conventional[kg/km]			weight [ton]	fc_hybrid [kg/km]	fc_reduction [%]
	crude method	optimization 2020	from euroFOT data		crude method	
9553	0.27	0.24	0.27	34.7	0.25	7.2
4387	0.30	0.27	0.30	36.8	0.28	8.2
16687	0.29	0.26	0.30	32.4	0.27	7.7
14793	0.33	0.30			0.29	11.8
14789	0.32	0.29	0.29	36.1	0.28	11.7
20299	0.31	0.28			0.29	8.2
16785	0.31	0.28	0.36	37.0	0.28	9.8
22205	0.38	0.35	0.43	40.1	0.34	12.4
d_re_CVL_HD_National_LCG	0.28	0.26			0.26	9.1
d_re_CVT_AGEO_TOHOKU_nobori	0.27	0.25			0.25	8.9
d_re_sx144a_Austria	0.35	0.33			0.30	14.2
d_re_sx285_Isere	0.36	0.33			0.33	9.9
d_re_sx521_Skoghall	0.28	0.26			0.26	9.1
d_re_sx538_Japan_amongthemountains1	0.33	0.32			0.26	19.0
d_re_sx565_vbc_LH3	0.38	0.33			0.34	9.1
d_re_sx576_ISC1	0.28	0.28			0.25	13.1
d_re_cvl_HD_highway_LCP	0.28	0.26			0.26	8.4
d_re_sx096_Goteborg_Alingsas	0.30	0.27			0.27	10.8
d_re_sx135_Frankfurt_Koblenz	0.30	0.27			0.27	9.6
d_re_sx140b_Ulm_Stuttgart	0.36	0.33			0.30	15.8
d_re_sx204_Goteborg_Uddevalla_1987	0.27	0.26			0.25	9.3
d_re_sx276_Mont_Blanc	0.34	0.33			0.28	18.3
d_re_sx564_vbc_LH1	0.31	0.29			0.28	10.4
d_re_sx594_US_I26_S_Hilly_65mph	0.30	0.26			0.29	5.4
zeroslope_d_re_sx538_Japan_amongthemountains1	0.19	0.18			0.18	3.0

The results of the conventional powertrain, when using the crude method, showed a good correlation (R^2 = 0.94) with the ones obtained with the optimization algorithm for a truck purchased year 2020.



27. Appendix – Pay back time calculation

The payback time, T_{payb}, is defined as the time where the reduced operating cost compensates the extra costs due to electrified sub systems. Payback time is here calculated according to (10)-(12).

$$(10) \qquad T_{\text{payb}} = -\frac{\ln(1 - \frac{I}{s} \cdot i)}{\ln(1+i)} \approx I/s \text{ (years)}$$

where i is the interest rate, s is the operating cost savings each year and I is the extra component cost.

$$(11) \qquad I = markup \cdot (price_{\text{gen}} + price_{\text{eldrive}} + price_{\text{batt}} + price_{\text{eladdon}} + price_{\text{masspen}}) \quad (€)$$

$$(12) \qquad s = \left(\left(c_{\text{FC}} - c_{\text{FC conv}}\right) - c_{\text{el}}\right) \cdot L_{\text{peryear}} \quad (€)$$

It is natural to think that the payback time requirement is in proportion to the economical lifetime. The consequence is that payback time of a taxi car (vehicle with short lifetime, approximately 3 years) should be much lower than for example a city bus, that has a lifetime of approximately 10 years.

Appendix – Simulation example

The purpose of this chapter is to study a simulation example more in detail and to show how the optimization tool is working. As example, the winning hybrid variant on the most common predominantly flat transport task is considered.

Simulation overview

Figure 33 shows the simulation along the driving cycle d_re_sx565_vbc_LH3. Top plot shows speed and altitude, middle plot shows demanded power on rear axle, engine power and battery power. A positive power value means power to move the vehicle forward whilst a negative power means braking or energy regeneration. Lower plot shows the SoC variation (black dotted lines show the max/min values of the SoC-range).
Figure 34 shows a zoomed version of Figure 33.

Comments about Figure 33 and Figure 34:

- The optimization tool makes sure the SoC level starts and ends at the same level (50%).
- Along the driving cycle, the demanded power is split up between engine and electric motor in a way so that the sum of fuel, electricity, battery replacement costs are minimized.
- When reaching a descent (e.g. at time 78 minutes, see Figure 34) the optimization tool has controlled the SoC level to the lower SoC-limit level (45%). By doing this, more brake energy can

be regenerated when proceeding the descent. Similar scenario also occurs at time 25 minutes and at 55 minutes.

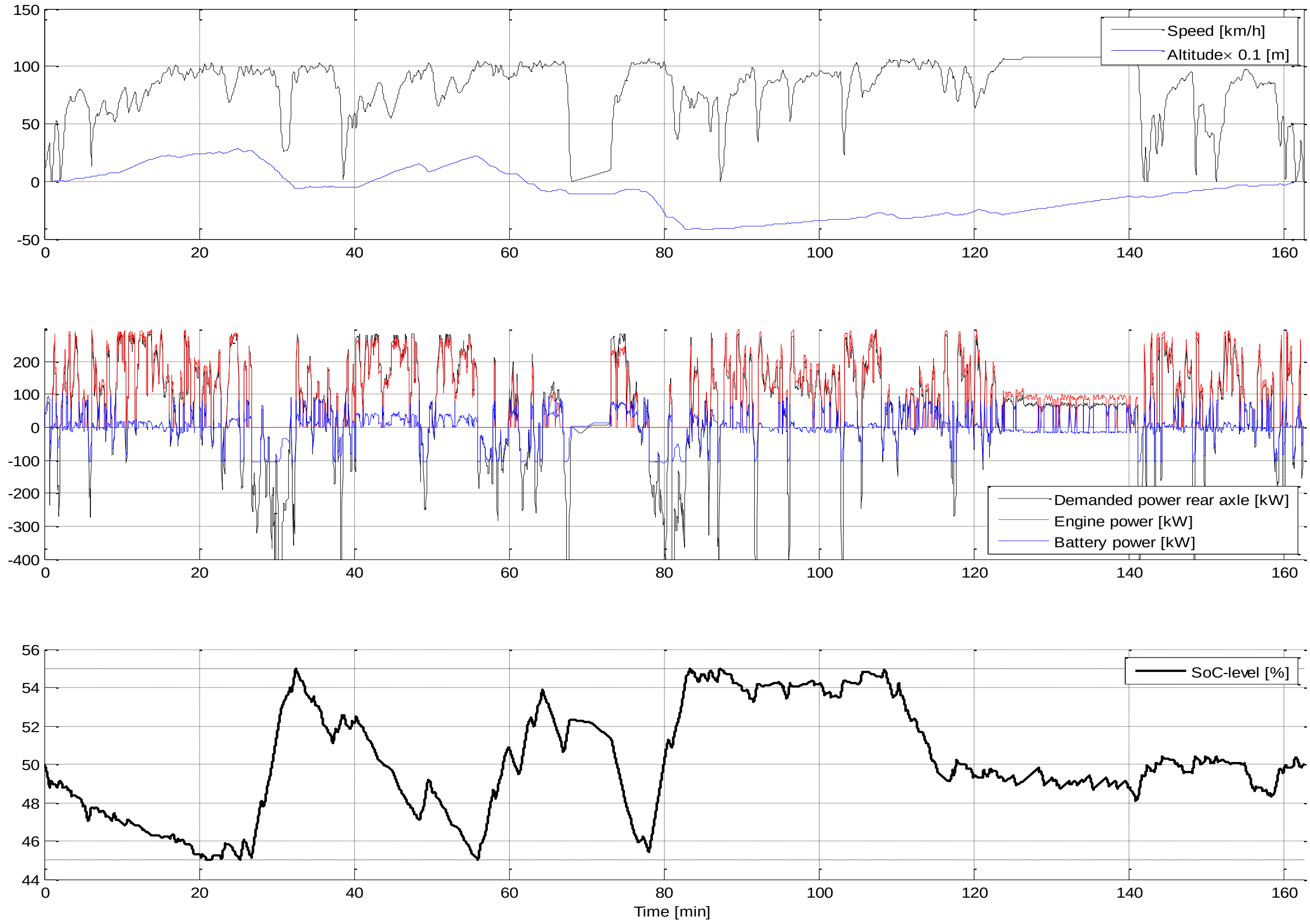


Figure 33. *Simulation example.*

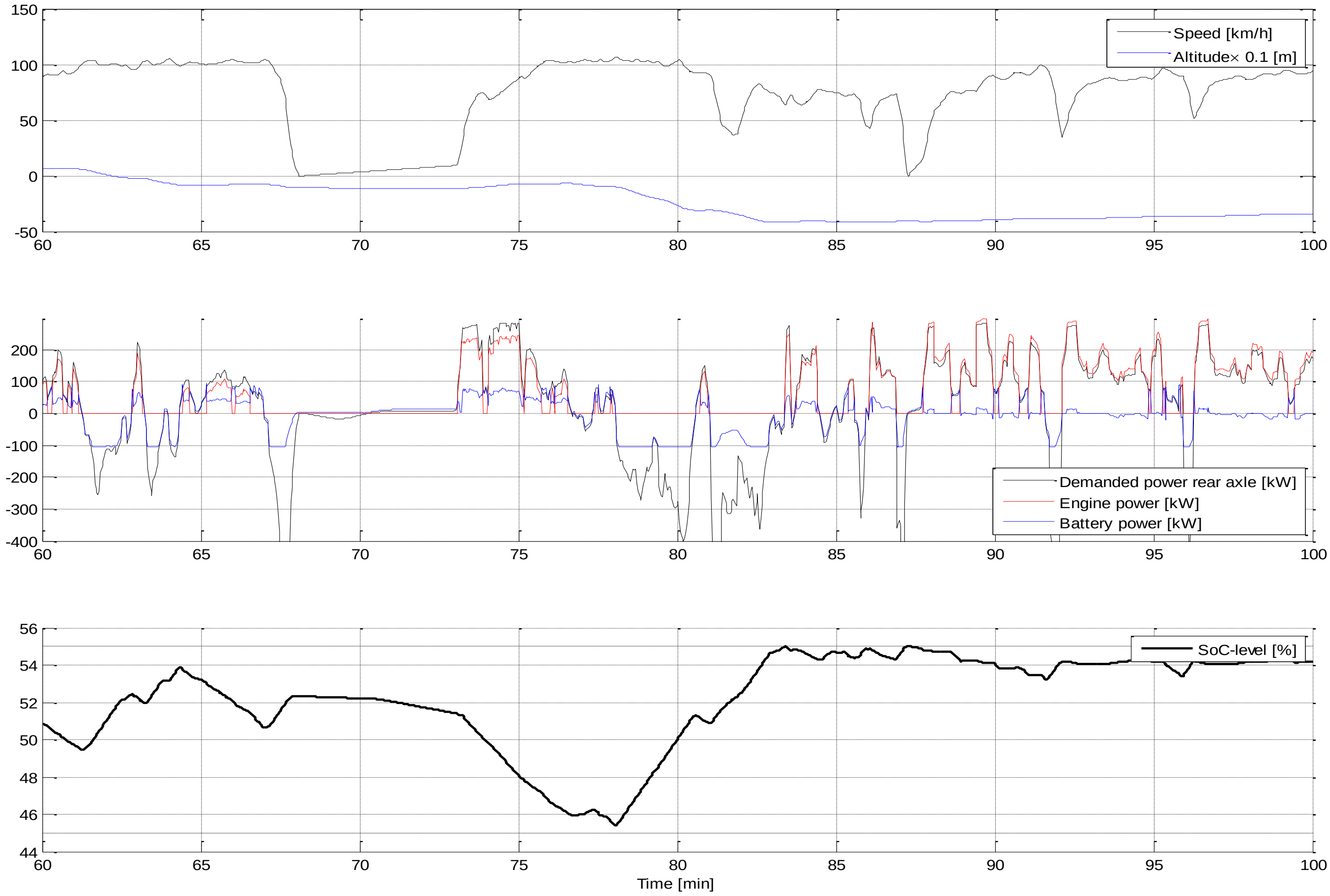


Figure 34. *Zoomed simulation example.*

ICE efficiency comparison

Figure 35 shows the engine power distribution for conventional and power distribution between engine and electric motor for hybrid. For the conventional, the engine is always on (at idle), therefore the operation time at 0 kW is quite high. For the hybrid, the engine is assumed to be turned off at braking or cruising. It can also be seen in the figure that the engine has less operation time at higher power rates for the hybrid, this due to that the electric motor supports the engine to propel the vehicle.

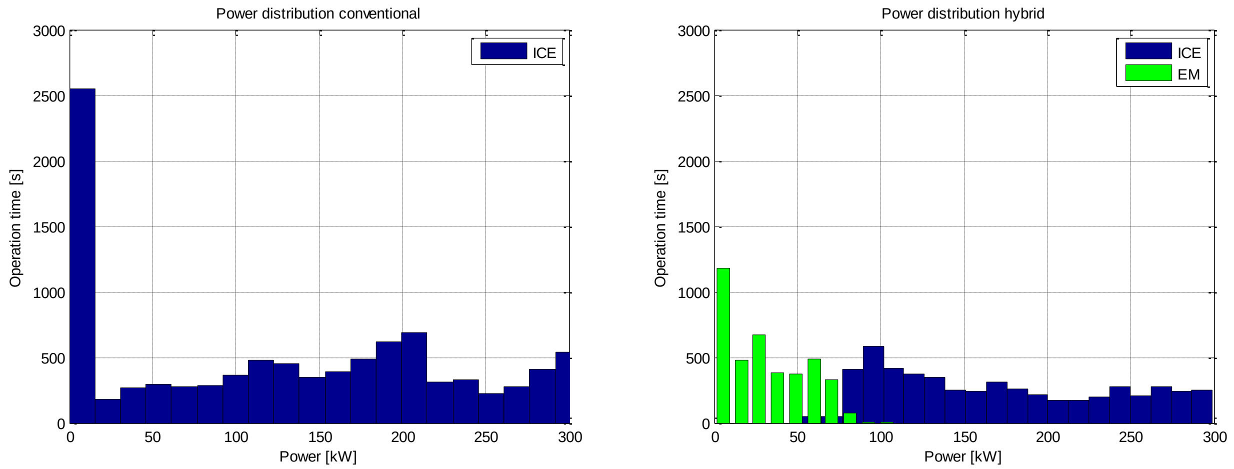


Figure 35. *Power distribution for conventional and hybrid.*

Figure 36 shows the demanded brake torque distribution on the rear axle of the vehicle for the driving cycle. In addition, for the hybrid variant, shown is also the regenerated power (battery power) distribution. As can be seen, most of the time during braking the regenerated power is limited to 100 kW. This indicates that the electric drive is undersized.

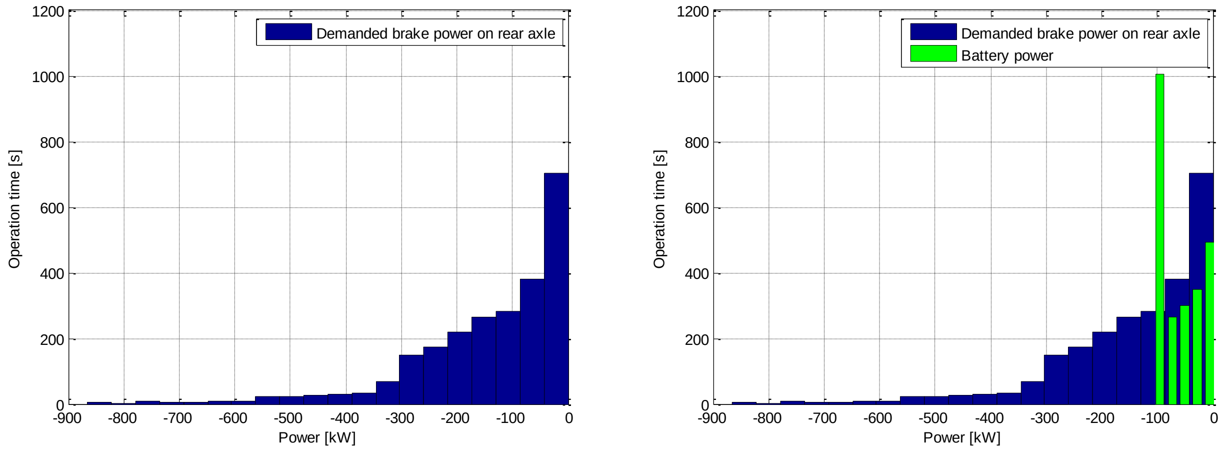


Figure 36. *Brake regeneration capability.*

Figure 37 shows the ICE efficiency distribution on the driving cycle for the hybrid and corresponding conventional. It might look strange that the efficiency is more often higher for the conventional compared to the hybrid. The results are logical though, the optimization tool does not optimize to maximize the engine efficiency, instead the optimization tries to minimize the total costs. Therefore, it might be advantageous to put the engine in a less efficient working point, to be able to for example partly use the electric motor to propel the vehicle.

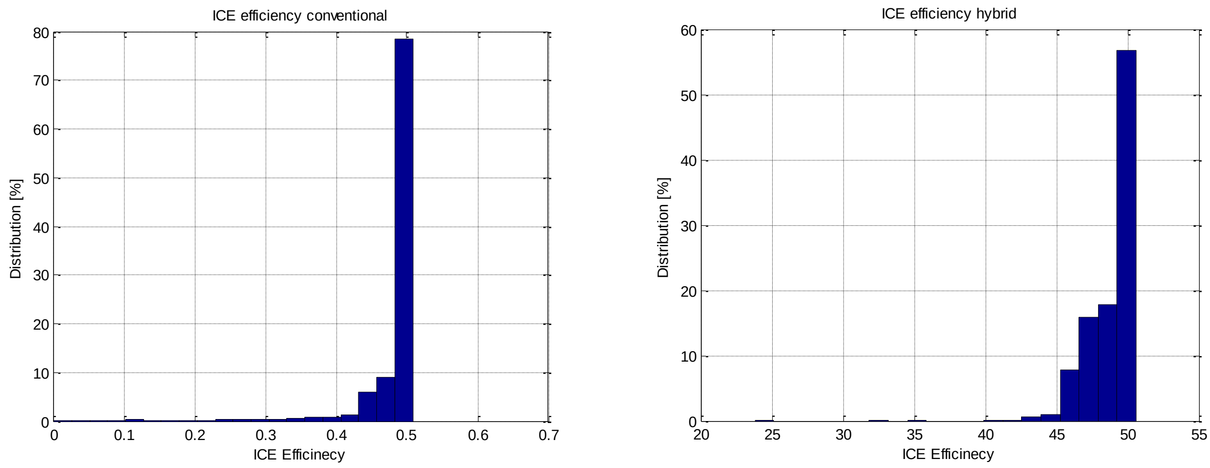


Figure 37. *ICE efficiency for conventional and hybrid.*

28. Appendix – Flat task type extreme fuel reduction

For the driving cycle d_re_sx594_US_I26_S_Hilly_65mph, which belongs to the Flat task group, a fuel reduction up to 45-50% could be seen in the results in Figure 14. This high fuel reduction is no error, it is due to that this driving cycle has very slow decelerations which leads to that almost all energy can be regenerated to the battery. Figure 38 shows an extract of the driving cycle which leads to the high fuel reduction. As can be seen the demanded brake power in the middle plot almost never goes below 100 kW. Therefore, it is possible for the battery to regenerate most of the brake power (no need of using the mechanical brakes), there are only losses due to efficiency losses in electric motor and battery.

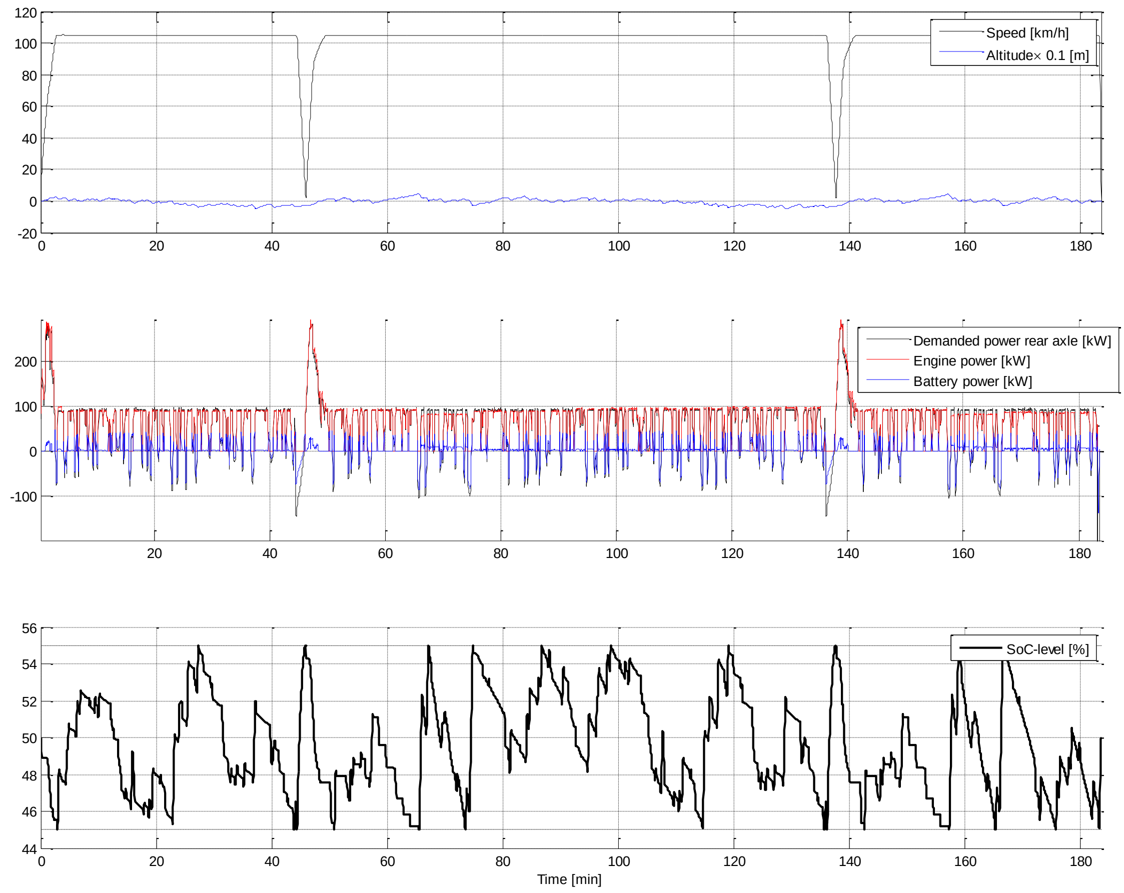


Figure 38. *Slow decelerations in driving cycle "cycle_d_re_sx594_US_I26_S_Hilly_65mph" leads to most brake energy can be regenerated.*

29. Appendix - Considered powertrain variants

Figure 39 and Figure 40 shows the studied powertrain topologies. For the two hybrid topologies, three engines and three battery sizes are evaluated. Table 9 includes a list of all variants.

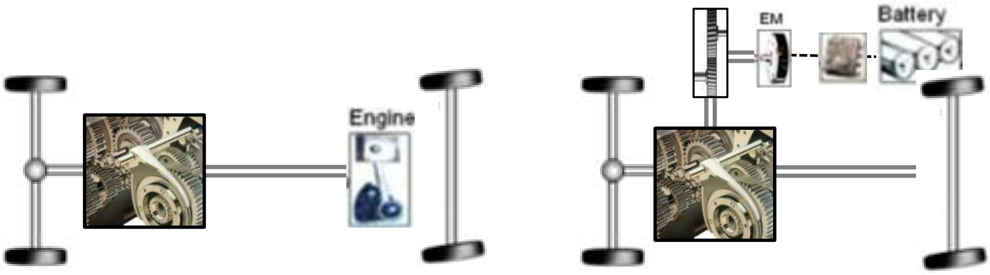


Figure 39. *Conventional powertrain (left) and hybrid with AMT-PS (right).*

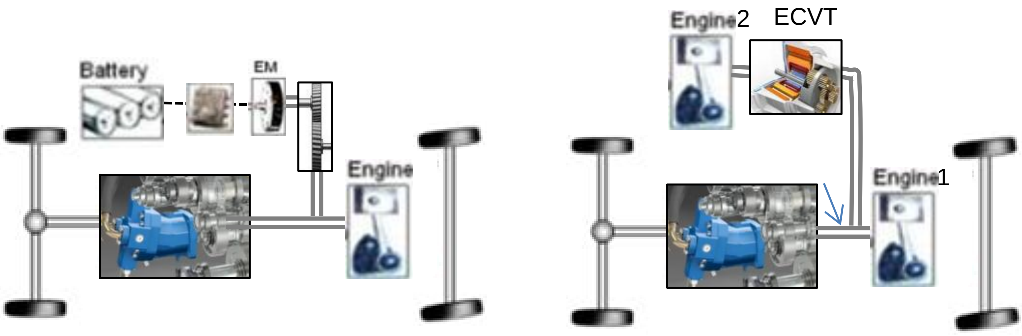
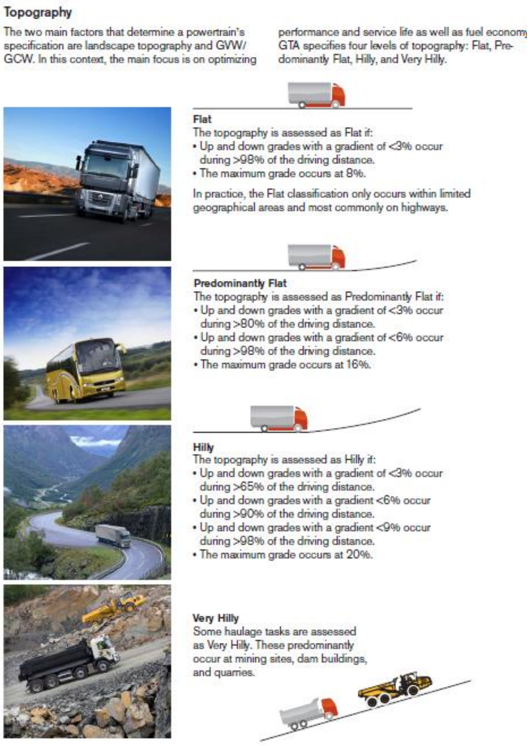


Figure 40. *Hybrid powertrain with HCVT (left) and dual engine (right).*

30. Appendix - GTA definition of topography

Figure 41 shows different topography types, very hilly is excluded in this study.



Topography

The two main factors that determine a powertrain's specification are landscape topography and GVW/GCW. In this context, the main focus is on optimizing performance and service life as well as fuel economy GTA specifies four levels of topography: Flat, Predominantly Flat, Hilly, and Very Hilly.

Flat
The topography is assessed as Flat if:
- Up and down grades with a gradient of <3% occur during >98% of the driving distance.
- The maximum grade occurs at 8%.

In practice, the Flat classification only occurs within limited geographical areas and most commonly on highways.

Predominantly Flat
The topography is assessed as Predominantly Flat if:
- Up and down grades with a gradient of <3% occur during >80% of the driving distance.
- Up and down grades with a gradient of <6% occur during >98% of the driving distance.
- The maximum grade occurs at 16%.

Hilly
The topography is assessed as Hilly if:
- Up and down grades with a gradient of <3% occur during >65% of the driving distance.
- Up and down grades with a gradient <6% occur during >90% of the driving distance.
- Up and down grades with a gradient <9% occur during >98% of the driving distance.
- The maximum grade occurs at 20%.

Very Hilly
Some haulage tasks are assessed as Very Hilly. These predominantly occur at mining sites, dam buildings, and quarries.

Figure 41. *Topography types.*