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Development of a Transport Application based Cost Model for the assessment of future commercial vehicle concepts

Florian Kleiner[1], Horst E. Friedrich
[1]Florian Kleiner (corresponding author) German Aerospace Center (DLR), Institute of Vehicle Concepts,
Pfaffenwaldring 38-40, florian.kleiner@dlr.de

Abstract

The Total Cost of Ownership and the payback period are main purchase criterions of fleet operators regarding the acquisition of new commercial vehicles. Therefore, critical success factors are purchase and operating costs. However, purchase and operating costs are highly individual depending on transport task, vehicle size and powertrain technology. In order to perform a comparable and transparent evaluation of competing powertrain technologies a development of a systemic and consistent evaluation model which considers the transport task, specific vehicle configuration and related costs is required. Within this study, a techno-economic evaluation approach for the assessment of future commercial vehicle concepts coping with the complexity of the road freight transportation sector is introduced which supports strategic decisions of fleet operators and manufacturers relating to investments in alternative commercial vehicle powertrain technologies considering specific requirements as to payload, volumetric load, driving range, vehicle cost and payback period. Furthermore, by the use of the transport application based cost model information to policy makers to what circumstances alternative commercial vehicle powertrain technologies reach competitiveness are generated. For demonstration reason exemplary use case and different powertrain concepts for a tractor-trailer combination with 40 tonnes of gross vehicle weight is analysed.

Keywords: Total Cost of Ownership, cost model, commercial vehicles, truck, electric vehicles, business case

1 Introduction

In order moving towards a competitive low carbon economy by 2050 in Europe, the transport sector is required to reduce its greenhouse gas (GHG) emissions by around 60%, compared to the level of 1990 [1]. Type-approval standards of motor vehicles and engines with respect to CO, HC, NO_x and PM emissions are in place and were tightened over the last decades for all kind of vehicles. In terms of carbon dioxide (CO_2) emission, limitations only exist for passenger cars and light commercial vehicles with a gross vehicle weight not exceeding 3.5 tonnes [2-3]. About one quarter of road transport CO_2 emissions are estimated to be produced by Heavy Duty Vehicles (HDVs) in Europe, which are expected to increase due to further growing freight transport activity [4-5]. According to the European Commission and in order to reach the targets set within the Transport White Paper, CO_2 emission of HDVs needs to be curbed [6]. For this reasons, a transition to low emission commercial vehicles is essential. Due to the highly diverse road freight transport vehicle market and its applications, a comparable evaluation of alternative vehicle technologies is complex.

The Total Cost of Ownership (TCO) and the payback period are main purchase criterions of fleet operators regarding the acquisition of new commercial vehicles [7-9]. Therefore, critical success factors are purchase and operating costs. However, purchase and operating costs are highly individual depending on transport tasks, vehicle size and powertrain technology. In order to perform a comparable and transparent evaluation of competing powertrain technologies a development of a systemic and consistent evaluation model which considers the transport task, specific vehicle configuration and related cost is required. Within this study, a techno-economic evaluation approach for the assessment of future commercial vehicle concepts coping with the complexity of the road freight transportation sector is introduced. The evaluation approach is implemented within a Transport Application Based Cost Model named TACMO. To ensure consistent and transparent data inputs as well as results, comprehensive data investigations and model calculations were performed. In contrast to existing cost analyses like [8, 10-17] the influence by using alternative powertrain technologies on vehicle payload and volumetric load capacity can be shown. Furthermore, it allows for detailed and comprehensive analyses of the cost structures of various commercial vehicle concepts with different powertrain technologies relevant for the German new commercial vehicle sales market. In addition, powertrain technology specific cost for maintenance and repair as well powertrain technology specific resale values are considered.

2 Method, data and results

TACMO using a four step approach in order to cope with the complexity of the road freight transport vehicle market. Figure 1 illustrates the work flow of TACMO. In the following subsections, work flow is explained, underlying data is shown and results are illustrated for alternative powertrain concepts of a tractor-trailer combination with 40t gross vehicle weight (GVW).

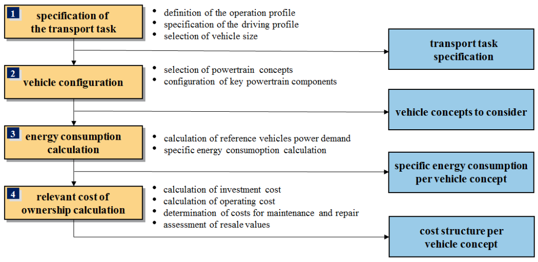


Figure 1: work flow of TACMO

2.1 Specification of the transport task

The transport task of a commercial vehicle is influenced by the type of goods to be conveyed, the application profile and the related driving characteristics. In order to allow for comparable analyses of different vehicle concepts, specification of the transport task is essential. Typical application profiles of road freight transport are urban delivery, regional delivery and long distance haulage [18]. Correlated areas of application are assumed to be up to 50 km, 51 to 150 km and more than 150 km respectively [19]. Correspondent driving characteristics are assumed to correlate with urban, regional and motorway driving cycles. Table 1 summarizes the transport task characteristics as described.

Depending on the vehicle size and type of goods transported e.g. bulk goods or packaged goods gravimetric and volumetric load varies [19].

Besides driving cycle characteristics like velocity over time and topographical data, the yearly mileage is a further important input parameter.

Table 1: transport task characteristics

transport task	1	2	3
application profile	urban delivery	regional delivery	long distance haulage
area of application	up to 50 km	51 to 150 km	more than 150 km
driving cycle	urban cycle	regional cycle	motorway cycle

The specification of transport task number three with the application profile long distance haulage for a tractor-trailer combination with 40 tonnes of gross vehicle weight is shown within Figure 2. The average yearly mileage of 100.000 km and the gravimetric as well as volumetric load data for vehicles with a gross vehicle weight of 40 t are based on information from the German Federal Office for Motor Vehicles [19, 86].

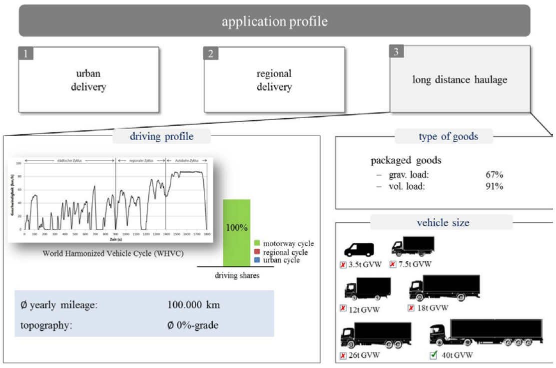


Figure 2: long distance haulage transport task specification

Assuming 265 working days per year average daily mileage requirement is 378 km. However, considering a maximum allowable driving time in Germany of 9 h for truck drivers and an average speed of 76.69 km/h (motorway driving cycle, see section 2.3) required maximum range is 691 km resulting in a maximum yearly mileage of about 180.000 km.

2.2 Vehicle configuration

Basically, TACMO allow for vehicle configuration of light and heavy duty vehicles. According to the European vehicle classification light duty vehicles are categorized as category N_1 and heavy duty vehicles are categorized as category N_2 or N_3 vehicles depending on the gross vehicle weight (GVW) [20]. The vehicle sizes with a GVW of 3,5t (N_1), 7.5t (N_2), 12t (N_2), 18t (N_3), 26t (N_3) and 40t (N_3, tractor-trailer) were identified as relevant for the German new commercial vehicle sales market and can be selected.

Based on the specification of the transport task and selection of vehicle size, selection of powertrain technology and vehicle configuration is required in order to determine relevant parameters for the energy consumption calculation. Therefore, vehicle characteristics like cross sectional area, air drag coefficient, rolling resistance coefficient and simulation mass needs to be defined. Considering the current state of the art and based on literature research cross sectional area, air drag coefficient, rolling resistance coefficient and the mass of glider was determined regarding the relevant vehicle sizes (see Table A.1 within the Appendix).

Vehicle simulation mass $m_{\mathrm{sim},i,j}$ is the sum of the vehicle payload $m_{\mathrm{payload},i,j}$ and the curb weight $m_{\mathrm{cw},i,j}$. It varies depending on vehicle size i and powertrain technology j.

$$m_{\mathrm{sim},i,j} = m_{\mathrm{payload},i,j} + m_{\mathrm{cw},i,j} \qquad (1)$$

Powertrain technologies considered are internal combustion diesel or natural gas engines (ICE-D, ICE-NG), mild, full and plug-in hybrid electric vehicles (MHEV, FHEV and PHEV), battery electric vehicles (BEV), range extended electric vehicles (REEV) and fuel cell electric vehicles (FCEV).

The curb weight $m_{\mathrm{cw},i,j}$ is the sum of n key powertrain related components $\sum_{c=1}^{n} m_{c,i,j}$ and the mass of the glider $m_{\mathrm{glider},i}$.

$$m_{\mathrm{cw},i,j} = \sum_{c=1}^{n} m_{c,i,j} + m_{\mathrm{glider},i} \qquad (2)$$

The vehicle payload $m_{\mathrm{payload},i,j}$ is calculated considering the gravimetric load GL in percentage and the difference between the gross vehicle weight $m_{\mathrm{GVW},i}$ and the curb weight $m_{\mathrm{cw},i,j}$.

$$m_{\mathrm{payload},i,j} = GL \cdot \left(m_{\mathrm{GVW},i} - m_{\mathrm{cw},i,j}\right) \qquad (3)$$

In addition to the mass calculation a calculation of the powertrain volume $V_{i,j}$ takes place based on the volume of key powertrain components considered $V_{\mathrm{c},i,j}$.

$$V_{i,j} = \sum_{c=1}^{n} V_{\mathrm{c},i,j} \qquad (4)$$

In order to allow for the bottom-up calculation of the simulation mass and powertrain volume as described above, a comprehensive investigation of the characteristics of key powertrain components based on factsheets and literature review was done. The gravimetric and volumetric default values used for the calculation of the vehicles curb weight and volume of the key powertrain components are attached to the Appendix (see Table A.2 and Table A.3). In addition, weight of exhaust aftertreatment as to vehicle category and powertrain concepts and effective volumetric load default values per vehicle category are attached to the Appendix (see Table A.4 and Table A.5).

Table 2 comprises the individual powertrain technology configurations, resulting simulation masses and powertrain volumes. Compared to the ICE-D powertrain concept, reduction in load capacity of the alternative powertrain concepts MHEV-D, FHEV-D, BEV and FCEV vary between 391 kg to 7.989 kg. Only the ICE-LNG concept allow for 20 kg additional loading capacity. The increase in powertrain volume for the concepts MHEV-D, FHEV-D, BEV and FCEV vary between 0.4 m³ to 3.3 m³. Only for the ICE-LNG concept a reduction in powertrain volume by 0.6 m³ take place. However, all vehicle concepts meet the gravimetric and volumetric load requirements of the transport task.

Table 2: configuration of vehicle concepts with a gross vehicle weight of 40t

		ICE-D	MHEV-D	FHEV-D	ICE-LNG	BEV	FCEV
ICE power max.	kW_{mech}	335	335	335	335	-	-
ICE torque max.	Nm	2.200	2200	2200	2.200	2.200	2.200
storage capacity - diesel	l_{diesel}	400	400	400	-	-	-
storage capacity - natural gas	kg_{NG}	-	-	-	180	-	-
storage capacity - hydrogen	kg_{350bar}	-	-	-	-	-	90
power of fuel cell system	kW_{el}	-	-	-	-	-	92
power of EM & PE 1	kW_{el}	-	60	120	-	335	335
power of EM & PE 2	kW_{el}	-	-	-	-	-	-
usable energy content of the battery system	kWh	-	5	10	-	700	5
mass of glider	kg	12.138					
curb weight	kg	14.156	14.547	14.856	14.136	22.145	15.045
gross vehicle weight	kg	40.000	40.000	40.000	40.000	40.000	40.000
load capacity	kg	25.844	25.453	25.144	25.864	17.855	24.955
difference compared to reference	kg	ref.	-391	-700	20	-7.989	-889
required payload (67% grav. load) $^{a)}$	kg	17.315					
simulation mass	kg	31.471	31.862	32.171	31.451	39.460	32.360
effective volumetric load	m³	90,0	89,6	89,3	90,6	86,7	86,7
required usable volume (91% vol. load) $^{b)}$	m³	82					
volume of powertrain concept	m³	3,2	3,5	3,8	2,6	6,4	6,4
difference compared to reference	m³	ref.	0,4	0,7	-0,6	3,3	3,3
cross sectional area	m²	10,00					
air drag coefficient	-	0,53					
rolling resistance coefficient	‰	6,00					

$^{a)}$payload based on ICE-D reference vehicle; $^{b)}$it is ssumed that higher volume of the powertrain directly affect the effective volumetric load

2.3 Energy consumption calculation

The distance based energy consumption E can be calculated by considering the energy demand of the outer and inner appearing driving resistances regarding an underlying driving profile.

$$E = \frac{\int \frac{1}{\eta_{\mathrm{TtW}}} \cdot [(m \cdot f_{\mathrm{R}} \cdot g \cdot \cos\alpha + \frac{\rho}{2} c_{\mathrm{W}} \cdot A \cdot v^2) + m(e_i \cdot a + g \cdot \sin\alpha)] \cdot v \cdot dt}{\int v \cdot dt} \quad (5)$$

A simplified reverse longitudinal dynamic calculation by using the equation of the driving resistances and average powertrain efficiency is implemented within TACMO in order to allow for vehicle concept individual calculation of the distance based energy consumption E. The fundamental relationships of the energy consumption calculation for conventional powertrain technologies using an internal combustion engine are shown within Figure 3. Depending on vehicle parameter and driving profile data, energy demand required at the wheel axle is calculated. Furthermore, load level is determined based on gear and axle drive ratios. By the use of tank to wheel (TtW) efficiencies distance based energy consumption is calculated. For alternative powertrain concepts with functionalities like stop-start, brake energy recovery or electric driving, the calculation methodology required modifications. Regarding a detailed explanation of the required modifications please see [51].

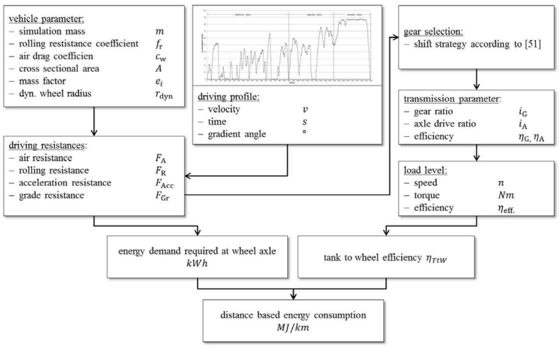


Figure 3: fundamental relationships of the energy consumption calculation

Fuel economy and exhaust emission test procedures differ between light and heavy duty vehicles. Reference and standardized cycle for light duty vehicles in Europe is the New European Driving Cycle (NEDC) [81]. The energy consumption and exhaust emissions of a vehicle are measured on a chassis dynamometer. In contrast, chassis dynamometer test of heavy duty vehicles were not performed and standardized test procedures in order to monitor the fuel economy are inexistent. Only engine exhaust emission certification tests take place according to the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC) requirements [82]. However, due to high discrepancies up to 38 % between the NEDC and real world consumption [83] the World-Harmonized Light-duty vehicles Test Procedure (WLTP) is planned to be established by 2017 [84]. For this reason the WLTP is additionally used for the energy consumption calculation of light duty vehicles. For heavy duty vehicles the World Harmonized Vehicle Cycle (WHVC) schedule is used, which is a chassis dynamometer test developed based on the same set of data used for the development of the World Harmonized Transient Cycle (WHTC) (see Figure 4). The

WHVC consists of three different driving cycles reflecting urban, rural and motorway driving characteristics.

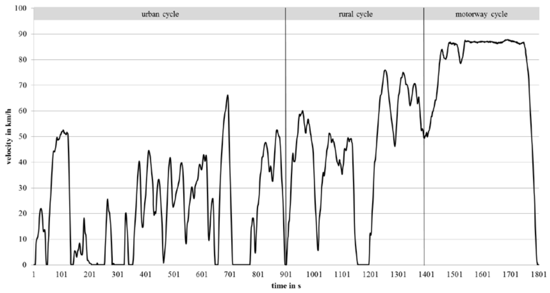


Figure 4: World Harmonized Vehicle Cycle used for heavy duty vehicle energy consumption calculation

The WHVC is not a standardized test procedure and is not used for regulatory testing. However, it is occasionally used for research purposes as shown within [24]. Key data regarding the WHVC are [85]:

- urban driving cycle: average speed of 21.26 km/h, maximum speed of 66.22 km/h, driving distance of 5,321 m
- rural driving cycle: average speed of 43.60 km/h, maximum speed of 75.92 km/h, driving distance of 5,818 m
- motorway driving cycle: average speed of 76.69 km/h, maximum speed of 87.80 km/h, driving distance of 8,919 m

As shown within Table 1 the cycles are assigned to the different transport tasks. According to the transport task specification (see Figure 2) and the vehicle configuration (see Table 2) resulting distance based TtW energy consumptions and ranges are shown within Figure 5. Table 3 contains the corresponding average TtW efficiencies.

Compared to the ICE-D as the reference, distance based energy consumption of the MHEV-D concept is 4 % less due to break energy recovery. The FHEV-D concept shows a distance based energy consumption reduction of 8 %. The stoichiometric combustion concept is considered as state of the art for heavy duty natural gas engines and results in lower efficiency compared to the lean combustion concept as state of the art for heavy duty diesel engines. Therefore, the distance based energy consumption of the ICE-LNG concept increases by 6 %. The BEV concept enables a distance based energy consumption reduction of 51 % and the FCEV concept by 20 %.

Table 3: TtW efficiencies per powertrain concept

	average TtW efficiency in %
ICE-D	36
MHEV-D	38
FHEV-D	40
ICE-LNG	34
BEV	74
FCEV	43

According to the results shown within Figure 5 all powertrain concepts fulfill the average daily mileage requirement of 378 km. However, the maximum daily mileage of 691 km cannot be reached by the ICE-LNG and the BEV concept. Nevertheless, due to the fast refuelling time of the ICE-LNG concept compared to the required long charging time of the BEV concept, the ICE-LNG concept would be able to cover the maximum daily driving range if a fuelling station is available.

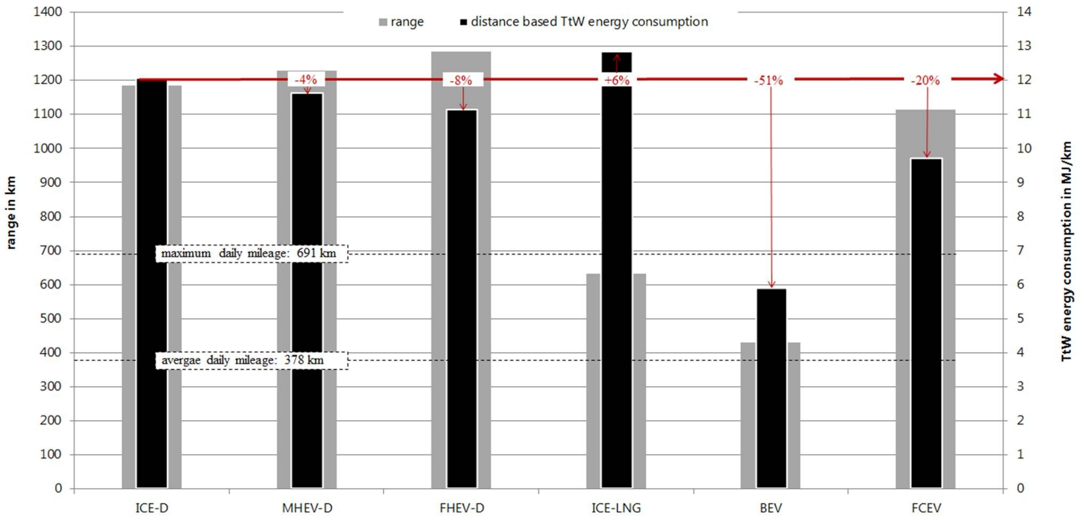


Figure 5: distance based energy consumption and range of vehicle concepts with a GVW of 40t

2.4 Relevant Cost of Ownership calculation

The total cost of ownership (TCO) method allows the evaluation of an investment from a particular supplier [87]. In the literature, several definitions of TCO can be found which are summarized within [88]. According to [89] a reason for the several existing definitions is that no model fits all purchase situations. Unique models developed specifically to consider whatever cost elements are most applicable to a particular purchase are necessary and must be adapted to the situation [89]. In terms of vehicle purchase situations TCO analyses gives an answer to the decision makers whether it is advantageous paying higher capital cost for advanced technology with lower operating cost over paying lower capital costs for conventional technology with higher operating cost [90]. The TCO calculation thus considers all customer related costs and is most important for new technology adoption. Especially, within the commercial vehicle business the relevance of calculating the TCO is of high importance, due to the intense competitive pressure on different markets [91]. As mentioned above unique models, developed specifically to consider whatever cost elements are most applicable to a particular purchase is necessary and must be adapted to the situation. Thus, in analogy to [92] the relevant cost of ownership (RCO) term is used and adapted for commercial vehicles in this study. RCO are calculated considering vehicle investment cost I^{v}, vehicle operating cost per year O^{v}, the resale value of the vehicle after service life $R(n)$, possible tax advantage $T(n)$, possible monetary subsidy S, investment cost I^{c} and yearly operating cost O^{c} of required private charging equipment. The RCO represent the final capital value of an investment depending on an expected service life n.

$$RCO = (1+z)^n \cdot (I^{\mathrm{v}} - S + I^{\mathrm{c}}) - R(n) - T(n) + \sum_{x=1}^{n} (1+z)^x \cdot (O^{\mathrm{v}} + O^{\mathrm{c}}) \quad (6)$$

Vehicle investment cost resulting by multiplication of the retail price equivalent (RPE) factor with the net vehicle investment cost NI^{v}. The RPE is a common used scaling factor which compares the net investment costs with all other factors that influence the final price of a vehicle [93]. Based on literature review the average RPE of 1.48 is used as default value [8, 10, 94].

The net vehicle investment costs are calculated by the sum of the total powertrain specific component cost I^{p} and the cost of the glider (rest of vehicle) I^{glider}. Powertrain specific component costs depending on the configuration of the key powertrain components a and related specific cost i. The underlying investment costs of the glider per vehicle category and the specific costs of key powertrain components are attached to the Appendix (see Table A.6 and Table A.7).

$$\begin{aligned} VIC &= RPE \cdot NI^{\mathrm{v}} = RPE \cdot \left(I^{\mathrm{glider}} + I^{\mathrm{p}}\right) \\ &= RPE \cdot \left(I^{\mathrm{glider}} + \textstyle\sum_{b=1}^{y} a_b \cdot i_b\right) \end{aligned} \quad (7)$$

Vehicle operating costs per year include yearly fix O^{fix} and variable cost $O^{\mathrm{var.}}$.

$$O^{\mathrm{v}} = O^{\mathrm{fix}} + O^{\mathrm{var.}} \quad (8)$$

Vehicle fix costs are vehicle tax, vehicle insurance and labour cost. Variable costs are energy consumption cost, cost for maintenance and repair and toll expenditures. The cost for maintenance and repair based on a bottom-up cost calculation model developed at the Institute of vehicle concepts. Same applies for the assessment of the resale value. The tax advantage is calculated considering a linear depreciation and the company tax rate r.

$$TA = \left[\sum_{x=1}^{n} (1+z)^x \cdot \frac{I^{\mathrm{v}} - S}{n}\right] \cdot r \quad (9)$$

Investment cost and operating cost for the private charging equipment (50 kW DC charger) is based on [98].

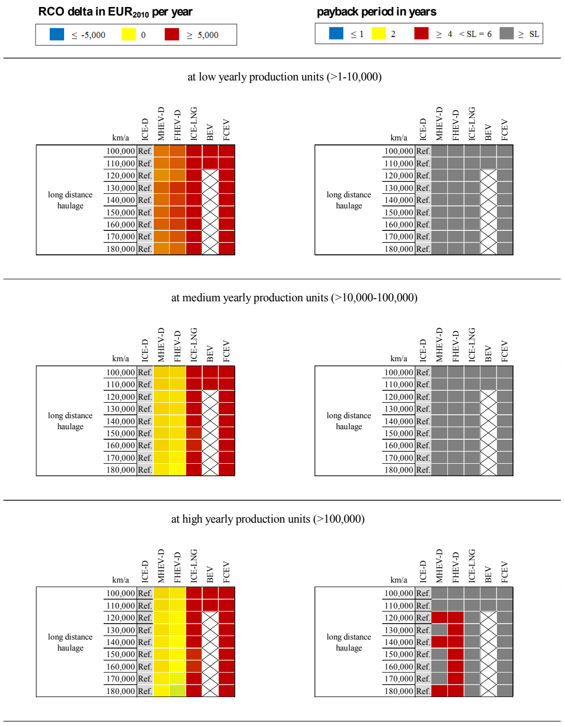
Beside the relevant cost of ownership, appropriate payback period is an important requirement of fleet operator and, therefore, affecting the technology adoption. The payback period PP is the duration of time required to recover the cost of an investment. Within this study the payback period in years is calculated by considering the difference in investment cost ΔI and operating cost ΔO of an alternative powertrain concept compared to the ICE –D, chosen as the reference vehicle.

$$PP = \frac{\Delta I}{\Delta O} \quad (10)$$

According to a survey of German logistician (n=119) a payback period of up to two years was requested by 88 %. Only for 12 % of the interviewees would accept a payback period of more than two years [99].

In the following two scenarios, an economy of scale scenario and an economy of scale and energy price scenario are investigated in order to illustrate the impact on the competitiveness of alternative powertrain technologies. The results of the economy of scale scenario (see Figure 6) show that for electrified conventional powertrain technologies like MHEV-D and FHEV-D at least medium yearly production units are required in order to almost achieve competitiveness. At high yearly production units and a mileage of 180.000 km per year only the FHEV-D concept has lower RCO compared to the reference vehicle. However, the payback period is greater than four years. All of the other powertrain concepts are not competitive and either does not allow for payback because of inexistent operating cost benefits or the payback period is greater than the service life. Due to range limitation and long charging times of the BEV concept feasibility is not given for yearly mileages of more than 110.000 km.

Figure 6: relevant cost of ownership comparison and payback periods of alternative powertrain concepts for a tractor-trailer combination with 40 tonnes of gross vehicle weight (economies of scale scenarios)


RCO delta in EUR_{2010} per year

payback period in years

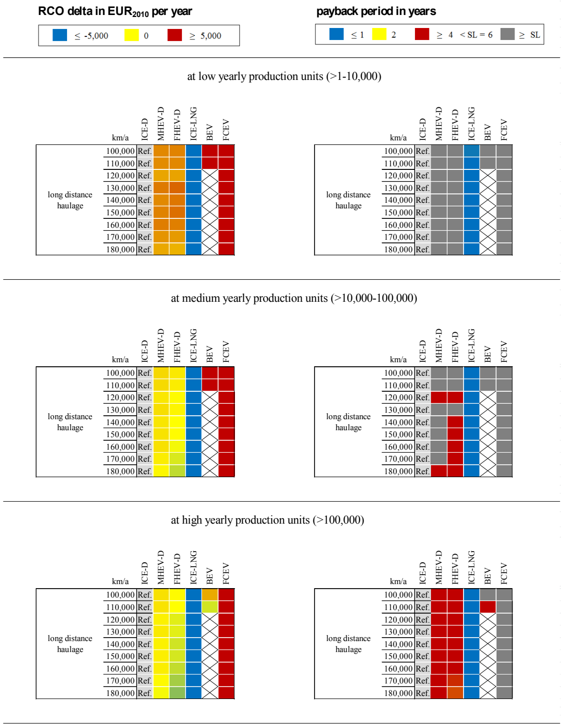
at low yearly production units (>1-10,000)

at medium yearly production units (>10,000-100,000)

at high yearly production units (>100,000)

When looking at the economy of scale and energy price scenario (see Figure 7) the ICE-LNG concept is most competitive already at low yearly production units and has payback periods of less than one year. Also the FHEV-D concept is cost competitive at medium yearly production units and a yearly mileage of 160.000 km but has a payback period between four and six years. At high yearly production units also the MHEV-D concepts reach cost competitiveness at a yearly mileage of 180.000 km. At a yearly mileage of 120.000 km it is the case for the FHEV-D concept. However, the payback periods of both concepts are between three and six years. The FCEV concept does not reach cost competitiveness in all scenarios. Main reasons for that are high costs for maintenance and repair as well as uncompetitive fuel cost. Interestingly the BEV concept reaches cost competitiveness at high production units and a yearly mileage of 110.000 km. Reasons for that are cost benefits regarding maintenance and repair and a competitive energy price.

Figure 7: relevant cost of ownership comparison and payback periods of alternative powertrain concepts for a tractor-trailer combination with 40 tonnes of gross vehicle weight (energy price and economies of scale scenarios)


RCO delta in EUR_{2010} per year

payback period in years

at low yearly production units (>1-10,000)

at medium yearly production units (>10,000-100,000)

at high yearly production units (>100,000)

Fundamental impact in terms of reaching competitiveness of alternative powertrain concepts, therefore, based rather on fuel or energy price policy than on production unit decisions. This is because the fuel cost account for about 30 % of the operating costs for heavy duty vehicles in long distance haulage operation and thus a major element of cost beside the cost for the truck driver. Yearly new vehicle registrations in Germany of tractor trailer are around 30,000 units and thus compared to passenger cars a significant lower quantity. However, production unit decision and energy price policy both are important regarding achieving competitiveness of alternative powertrain technologies.

The relevant scenario parameters like cost developments of key powertrain components, costs for maintenance and repair, resale values and fuel price assumptions for the different powertrain concepts considered are attached to the Appendix (see Table A.8, Table A.9, Table A.10 and Table A.11)

3 Conclusion

A transport application based cost model was introduced using a four step approach that allows for a consistent and detailed comparison of future commercial vehicle powertrain concepts different vehicle categories. Comprehensive literature research was done to determine gravimetric and volumetric performance parameter regarding key powertrain components of alternative powertrain concepts describing the current state of the art. The relevant cost of ownership term and related cost composition most relevant for the commercial vehicle purchase decision were defined. Furthermore, cost data was gathered through additional comprehensive literature research in order to undertake detailed bottom-up vehicle investment cost calculation depending on individual vehicle configuration. The systematic approach presented allows not only for the demonstration of powertrain concept and configuration depended impact on payload, volumetric load and driving range but also allow for the identification of cost drivers. For demonstration reason, exemplary use case and different powertrain concepts for a tractor-trailer combination with 40 tonnes of gross vehicle weight was analysed. Concluding, TACMO was developed in order to support strategic decisions relating to investments in alternative commercial vehicle powertrain technologies considering specific requirements as to payload, volumetric load, driving range, vehicle costs and payback period. Furthermore, TACMO generates information to policy makers on what conditions alternative commercial vehicle powertrain technologies reach competitiveness and is able to investigate policy impacts like the use of subsidies or tax exemptions for example.

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Authors

Florian Kleiner, researcher at the German Aerospace Center (DLR). He studied Business Administration and Engineering at Pforzheim University and the University of Technology Sydney (UTS). After graduating his Master degree regarding energy management with specialization in renewable energy at Trier University of Applied Sciences, he is working at the DLR Institute of Vehicle Concepts in the department of Vehicle Systems and Technology Assessment.

Prof. Dr. H. E. Friedrich is Director of the Institute of Vehicle Concepts at the German Aerospace Center in Stuttgart. The institute develops concepts of road and rail vehicles of next generations. The research fields are Alternative Power Trains and Energy Conversion as well as Light Weight Design and Hybrid Construction methods. At the same time he became professor at the University of Stuttgart and he is lecturer at the Technical University of Berlin.

Appendix

Table A.1: vehicle parameters used within TACMO [20-26]

Vehicle category [a] & Gross Vehicle Weight (GVW)	Cross-sectional area in m^2	Air drag coefficient	Rolling resistance [d] coefficient in ‰	Mass of glider [c] in kg
N_1: 3.5t GVW	3.5	0.37	8.50	1,446
N_2: 7.5t GVW	7.0	0.45	7.35	3,555
N_2: 12t GVW	8.0	0.50	7.35	5,104
N_3: 18t GVW	9.0	0.55	6.00	9,220
N_3: 26t GVW	9.0	0.55	6.00	9,613
N_3-TT [b]: 40t GVW	10.0	0.53	6.00	12,138

[a] European vehicle category according [21]; [b] tractor-trailer combination; [c] the glider comprises all components except for the powertrain of a vehicle. These are in analogy to [14] the chassis (frame, suspension, wheel, tires, etc.) and the body (platform, cab, etc.). Regarding the N3-TT, glider mass includes the trailer weight. Reference glider mass is derived from the average given curb weight of current available conventional diesel vehicles by subtracting the weight of powertrain relevant components taking gravimetric performance parameters shown within Table A.2 into account. [d] according to [22] and [23]; N_1: tire class C1; N_2: tire class C2 and N_3: tire class C3; efficiency classes considered for calculation of default value: A, B, C

Table A.2: gravimetric performance parameters regarding powertrain components considered

	unit	category	value	sources
large diesel engine [a]	kW/kg	average [h]	0.318	[27-37]
		low	0.270	
		high	0.370	
small diesel engine [b]	kW/kg	average [h]	0.576	[38-39], expert interview [l]
		low	0.50	
		high	0.70	
large natural gas engine [c]	kW/kg	average [h]	0.285	[40-42]
		low	0.250	
		high	0.337	
small natural gas engine [d]	kW/kg	default value	0.39	[43]
e-motor [e]	kW/kg	average [h]	1.42	[44-49]
		low	1.18	
		high	1.76	
power electronics [j]	kW/kg	average [h]	6.40	[46-49, 52-53]
		low	2.50	
		high	10.32	
battery system (high energy) [i]	kWh/kg	average [h]	0.107	[54-56]
		low	0.100	
		high	0.112	
battery system (high power) [m]	kWh/kg	default value	0.043	[57]
fuel cell system [k]	kW/kg	average [h]	0.324	[58-60]
		low	0.218	
		high	0.379	
Hydrogen storage system 700 bar [f]	kg H_2/kg	average [h]	0.051	[61-62]
		low	0.048	
		high	0.054	
hydrogen storage system 350 bar [f]	kg H_2/kg	average [h]	0.044	[61-62]
		low	0.040	
		high	0.048	
hydrogen storage system liquid [f]	kg H_2/kg	default value	0.060	[61]
diesel storage system [g]	l/kg	average [h]	4.34	[9, 63]
		low	3.67	
		high	5.00	
natural gas storage system 200 bar [l]	kg NG/kg	default value	0.273	[61]
natural gas storage system liquid [l]	kg NG/kg	default value	0.532	[61]

[a]considered number of engines: 13, engine displacement bandwidth: 4l-13l, Range of engine performance: 152kW-375kW, EUR VI emission standard; [b]considered number of engines: 4, engine displacement: 1.6l-3l, Range of engine performance: 77kW-140kW, EUR VI emission standard; [c]considered number of engines: 3, engine displacement bandwidth: 6l-8l, Range of engine performance: 147kW-206kW, EEV emission standard; [d]considered number of engines: 1,engine displacement: 3l, engine performance: 100kW; [e]values regarding permanent magnet synchronous machine (PSM); hybrid synchronous machine (HSM) and current excited synchronous machine (SSM); considered number of PSM/HSM/SSM: 6; Nominal power range: 60-150 kW; nominal torque: 220Nm-400Nm; [f]this refers to the entire storage system, including the storage vessel, piping, valves, and anything else required by the storage system to function properly as well as the storage medium; literature values [g]only regarding the storage vessel, not including energy carrier; literature values [h]arithmetic mean of sources; [i]Lithium Nickel Manganese Cobalt Oxide (NMC) technology, C-Rate: 2-5; considered number of systems: 1 [j]PSM/HSM Controller: Operating voltage 450-750VDC; current limitation DC: 350-500A, Liquid cooled; considered number of systems: 9 [k]Medium & Heavy duty polymer electrolyte membrane fuel cell system (PEM), considered numbers of systems: 3; [l]this refers to the entire storage system, including the storage vessel, piping, valves, and anything else required by the storage system to function properly, but it is assumed without the storage medium; literature values; [m]Lithium Nickel Manganese Cobalt Oxide (NMC) technology, C-Rate: 10; considered number of systems: 1

Table A.3: volumetric performance parameters regarding the powertrain components considered

	unit	category	value	sources and notes
large diesel engine [a]	kW/m^3	average [f]	221	[29-34]
		low	153	
		high	259	
small diesel engine	kW/m^3	default value	287	own assumption based on large gas to diesel engine correlation
large natural gas engine [b]	kW/m^3	average [f]	199	[40-42]
		low	170	
		high	238	
small natural gas engine [c]	kW/m^3	default value	258	[43]
xxhaust aftertreatment (EUR VI) [k]	kW$_{engine}$/m^3	default value	674	derived from [63]
e-motor [d]	kW/m^3	average [f]	2886	[44, 46-49, 52]
		low	1069	
		high	5023	
power electronics [h]	kW/m^3	average [f]	7483	[46-49, 52-53]
		low	2550	
		high	12501	
battery system (high energy) [g]	kWh/m^3	average [f]	174	[53-56]
		low	144	
		high	200	
battery system (high power) [l]	kWh/m^3	default value	57	[57]
fuel cell system [i]	kW/m^3	average [f]	217	[58-60]
		low	204	
		high	227	
hydrogen storage system 700 bar [e]	kg H$_2$/m^3	average [f]	26.3	[61-62]
		low	25.6	
		high	27.0	
hydrogen storage system 350 bar [e]	kg H$_2$/m^3	average [f]	16.1	[61-62]
		low	15.0	
		high	17.2	
hydrogen storage system liquid [e]	kg H$_2$/m^3	default value	36	[61]
diesel storage system	l/m^3	average [f]	695	[10]
		low	500	
		high	889	
natural gas storage system 200 bar [e]	kg NG/m^3	default value	108	[61]
natural gas storage system liquid [e]	kg NG/m^3	default value	237	[61]

[a]considered number of engines: 9, engine displacement bandwidth: 4l-13l, Range of engine performance: 152kW-353kW, EUR VI emission standard; [b]considered number of engines: 3, engine displacement bandwidth: 6l-8l, Range of engine performance: 147kW-206kW, EEV emission standard; [c]considered number of engines: 1, engine displacement: 3l, engine performance: 100kW; [d]values regarding permanent magnet synchronous machine (PSM); hybrid synchronous machine (HSM) and current excited synchronous machine (SSM); considered number of PSM/HSM/SSM: 6; Nominal power range: 60-150 kW; nominal torque: 220Nm-400Nm; [e]this refers to the entire storage system, including the storage vessel, piping, valves, and anything else required by the storage system to function properly, as well as the storage medium; literature values [f]arithmetic mean of sources; [g]Lithium Nickel Manganese Cobalt Oxide (NMC) technology, C-Rate: 2-5; considered number of systems: 1 [h]PSM/HSM Controller: Operating voltage 450-750VDC; current limitation DC: 350-500A, Liquid cooled; considered number of systems: 7 [i]Medium & Heavy duty polymer electrolyte membrane fuel cell system (PEM), considered numbers of systems: 3; [j]data derived from ZF transmission program for commercial vehicles: Ecolite, AS Tronic lite, AS Tronic mid, AS Tronic, Ecosplit; considered number of transmissions: 20; [k]proportional relationship between engine displacement and effort for exhaust aftertreatment is assumed; [l]Lithium Nickel Manganese Cobalt Oxide (NMC) technology, C-Rate: 10; considered number of systems: 1

Table A.4: weight of exhaust aftertreatment as to vehicle category and powertrain concepts

vehicle category [a] & Gross vehicle Weight (GVW)	weight of exhaust aftertreatment [c][kg]			sources
	ICE-D	ICE-NG	HEV	
N_1: 3.5t GVW	50	15	50	estimated values based on [65-67]
N_2: 7.5t GVW	85	15	85	
N_2: 12t GVW	100	25	100	
N_3: 18t GVW	150	25	150	
N_3: 26t GVW	150	25	150	
N_3-TT [b]: 40t GVW	150	25	150	

[a]European vehicle category according [21]; [b]traction trailer; [c]only relevant for vehicle with combustion engine; ICE-D: covering all systems necessary for EUR VI emission standard: oxidation catalytic converter, diesel particulate filter, selective catalytic reduction; ICE-NG: covering all systems necessary for EEV emission standard: three-way catalytic converter; HEV: for simplification reasons same as for the ICE-D

Table A.5: effective volumetric load default values per vehicle category

vehicle category [a] & Gross vehicle Weight (GVW)	unit	default value	sources
N_1: 3.5t GVW	m^3	13 [a]	[68-69]
N_2: 7.5t GVW		20 [b]	[70]
N_2: 12t GVW		40 [b]	[71-74]
N_3: 18t GVW		50 [b]	[75-77]
N_3: 26t GVW		50 [b]	[75-77]
N_3-TT [b]: 40t GVW		90 [c]	[78-80]

[a]default value relating to transporter GVW 3.5 tons (Crafter, Movano, Sprinter, Transit); considered number of vehicles: 4; [b]default value relating to standard box body; considered number of boxes: 7 [c]default value relating to standard box trailer (3-axle); considered number of trailers: 4

Table A.6: investment costs of the glider per vehicle category

	unit	category	value	sources
glider N_1: 3.5t GVW	€$_{2010}$	average [a]	15,125	[12-13]
		low	12,250	
		high	18,000	
glider N_2: 7.5t GVW	€$_{2010}$	average [a]	21,563	
		low	18,000	
		high	25,125	
glider N_2: 12t GVW	€$_{2010}$	average [a]	32,563	
		low	25,125	
		high	40,000	
glider N_3: 18t GVW	€$_{2010}$	average [a]	51,000	
		low	40,000	
		high	62,000	
glider N_3: 26t GVW	€$_{2010}$	average [a]	51,000	
		low	40,000	
		high	62,000	
glider N_3-tractor: 40t GVW	€$_{2010}$	average [a]	56,250	
		low	52,500	
		high	60,000	
trailer N_3: 40t GVW [b]	€$_{2010}$	average [a]	20,585	[95-97]
		low	18,784	
		high	23,005	

[a]arithmetic mean of sources; [b]net values regarding trailers of Krone, Koegel, Schmitz Cargobull and Kaessbohrer

Table A.7: specific cots of key powertrain components

	unit	category	value	sources and notes
large diesel engine	€$_{2010}$/kW	average [a]	56.5	[10, 13, 100]
		low	37.4	
		high	75.6	
small diesel engine	€$_{2010}$/kW	average [a]	43.2	[12-13, 100]
		low	33.1	
		high	53.3	
large natural gas engine	€$_{2010}$/kW	average [a]	71.2	[12-13]
		low	42.2	
		high	71.2	
small natural gas engine	€$_{2010}$/kW	average [a]	37.7	[12-13, 100]
		low	26.7	
		high	48.6	
e-motor	€$_{2010}$/kW	default value		based on DLR cost model; depending on machine type, power and production units
power electronics	€$_{2010}$/kW	default value		based on DLR cost model; depending on machine type, power and production units
battery system (high energy)	€$_{2010}$/kWh	default value		based on DLR cost model; depending on machine type, power and production units
battery system (high power)	€$_{2010}$/kWh	default value		based on DLR cost model; depending on machine type, power and production units
fuel cell system	€$_{2010}$/kW	default value		based on DLR cost model; depending on machine type, power and production units
hydrogen storage system 700 bar [b]	€$_{2010}$/kWh	default value	31.1	[101]
hydrogen storage system 350 bar [b]	€$_{2010}$/kWh	default value	28.1	[101]
diesel storage system	€$_{2010}$/l	average [a]	2.0	[13, 100]
		low	1.4	
		high	2.5	
natural gas storage system 200 bar	€$_{2010}$/kWh	default value	3.7	[13, 100]
natural gas storage system liquid	€$_{2010}$/kWh	default value	5.1	[102]
exhaust aftertreatment (EUR VI) ICE-D	€$_{2010}$/kg$_{\text{curb weight}}$	default value	0.67	[12]
exhaust aftertreatment (EUR VI) ICE-NG	€$_{2010}$/kg$_{\text{curb weight}}$	default value	0.33	own assumption
gearbox AMT	€$_{2010}$/kg	default value	18.5	[103]
gearbox MT	€$_{2010}$/kg	default value	14.9	[103]

[a]arithmetic mean of sources; [b]hydrogen tank system costs relating to single tank system and hydrogen storage capacity of 5.6 kg

Figure A.8: cost parameters of key powertrain components depending on production units
(based on bottom-up cost model calculations)

		yearly production units		
powertrain component	unit	low (>1-10,000)	medium (>10,000-100,000)	high (>100,000)
e-motor	€$_{2010}$/kW	20.0	7.4	5.2
power electronics	€$_{2010}$/kW	22.7	8.8	6.0
battery system (high energy)	€$_{2010}$/kWh	640	395	182
battery system (high power)	€$_{2010}$/kWh	1,400	1,120	864
fuel cell system	€$_{2010}$/kW	821	192	51
natural gas storage system liquid	€$_{2010}$/kWh	5.1	4.5	3.8
hydrogen storage system 350 bar	€$_{2010}$/kWh	28.1	16.7	11.8

Figure A.9: costs for maintenance and repair in EUR$_{2010}$/km per powertrain concept and yearly mileages
(based on bottom-up cost model calculations)

yearly mileage	production units	ICE-D	MHEV-D	FHEV-D	ICE-LNG	BEV	FCEV
100,000	low	0.14	0.14	0.14	0.14	0.10	0.24
	medium		0.14	0.14	0.14	0.10	0.19
	high		0.14	0.14	0.14	0.10	0.16
110,000	low	0.14	0.14	0.14	0.13	0.09	0.23
	medium		0.14	0.14	0.13	0.09	0.18
	high		0.14	0.14	0.13	0.09	0.15
120,000	low	0.14	0.14	0.14	0.13	-	0.22
	medium		0.14	0.14	0.13	-	0.17
	high		0.14	0.14	0.13	-	0.15
130,000	low	0.14	0.14	0.15	0.14	-	0.34
	medium		0.14	0.14	0.14	-	0.20
	high		0.14	0.14	0.14	-	0.16
140,000	low	0.15	0.15	0.15	0.14	-	0.33
	medium		0.15	0.15	0.14	-	0.20
	high		0.14	0.15	0.14	-	0.16
150,000	low	0.17	0.17	0.18	0.15	-	0.32
	medium		0.17	0.17	0.15	-	0.20
	high		0.17	0.17	0.15	-	0.16
160,000	low	0.16	0.17	0.17	0.15	-	0.30
	medium		0.17	0.17	0.15	-	0.19
	high		0.16	0.16	0.15	-	0.15
170,000	low	0.17	0.17	0.18	0.15	-	0.54
	medium		0.17	0.17	0.15	-	0.33
	high		0.17	0.17	0.15	-	0.26
180,000	low	0.17	0.17	0.17	0.15	-	0.52
	medium		0.17	0.17	0.15	-	0.32
	high		0.17	0.17	0.15	-	0.25

Figure A.10: resale values in EUR_{2010} per powertrain concept and yearly mileages
(based on own calculation approach for the assessment of resale values for alternative powertrain concepts)

yearly mileage	production units	ICE-D	MHEV-D	FHEV-D	ICE-LNG	BEV	FCEV
100,000	low	44,358	35,987	39,353	14,934	0	0
	medium		34,803	36,985	14,750		
	high		34,268	35,914	14,568		
110,000	low	39,342	30,908	33,799	11,748	0	0
	medium		29,891	31,765	11,603		
	high		29,431	30,846	11,460		
120,000	low	34,893	26,546	29,029	9,241	-	0
	medium		25,673	27,282	9,127		
	high		25,278	26,492	9,015		
130,000	low	30,947	22,800	24,932	7,269	-	0
	medium		22,049	23,432	7,179		
	high		21,710	22,753	7,091		
140,000	low	27,448	19,582	21,414	5,718	-	0
	medium		18,938	20,125	5,648		
	high		18,646	19,542	5,578		
150,000	low	24,344	16,818	18,391	4,498	-	0
	medium		16,265	17,285	4,443		
	high		16,015	16,784	4,388		
160,000	low	21,591	14,445	15,796	3,538	-	0
	medium		13,969	14,845	3,495		
	high		13,755	14,415	3,452		
170,000	low	19,150	12,406	13,567	2,783	-	0
	medium		11,998	12,750	2,749		
	high		11,813	12,381	2,715		
180,000	low	16,984	10,655	11,652	2,189	-	0
	medium		10,305	10,951	2,162		
	high		10,146	10,634	2,136		

Figure A.11: fuel price assumptions at fueling station

	unit	economy of scale scenario	economy of scale and energy price scenario
diesel	€_{2010}/l	0.98	1.25
	€_{2010}/kWh	0.10	0.13
electricity	€_{2010}/kWh	0.17	0.10
liquefied natural gas	€_{2010}/kg	1.30	0.90
	€_{2010}/kWh	0.10	0.07
hydrogen	€_{2010}/kg	9.50	6.00
	€_{2010}/kWh	0.28	0.18