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Maintenance & Repair Cost Calculation and Assessment of Resale Value for Different Alternative Commercial Vehicle Powertrain Technologies

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Summary

For detailed evaluation of the Total Cost of Ownership, expenditures for Maintenance & Repair as well as the resale value are important to consider and should not be neglected. However, information on Maintenance & Repair costs as well as residual values for commercial vehicles with alternative powertrains is missing and data on this issue is rare. There is a lack of information and consolidated knowledge. In order to enable a holistic cost assessment for commercial vehicles, a comprehensive M&R cost model was developed by the use of a bottom-up approach, considering 46 individually assessed components regarding maintenance and 24 individually assessed components regarding repair as well as different inspections. It enables specific M&R cost calculations for different alternative commercial vehicle powertrain technologies of different vehicle sizes. In addition, an approach in order to assess the resale value for different alternative commercial vehicle powertrain technologies is introduced. Exemplary results are presented for different powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton and a rigid truck in urban operation with a gross vehicle weight of 12 ton. Altogether, by the use of the M&R methodology and the resale value approach required data in order to enable a holistic cost assessment for commercial vehicles can be provided.

Keywords: LCC (Life Cycle Cost), EV (electric vehicle), freight transport, heavy-duty, medium-duty

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1 Introduction

According to the transport white paper of the European Commission, the transport sector is required to reduce its greenhouse gas (GHG) emissions by around 60%, compared to the level of 1990, in order to reach a competitive low carbon economy by 2050 [1]. In order to improve local air quality, the number of cities throughout the European Union increases which are implementing some form of driving restrictions e.g. implementation of low-emission zones, introduction of emission tolls, ban on driving depending on vehicle size and weight, etc. [2]. For this reasons, a transition to low emission commercial vehicle technologies is essential which at the same time maintains or improves an efficient urban freight transport system. However, the market uptake of low emission commercial vehicles like hybrid electric vehicles

(HEV), battery (BEV) or fuel cell electric vehicles (FCEV) is slow. In Germany, as one of the major freight haulage and sales market countries within Europe [3], the vehicle stock of low emission commercial vehicle technology like natural gas, hybrid, battery or fuel cell, was below one percent in 2014 [4]. Sporadically, fleet operators set individual CO_2-emission targets and invested in new vehicle technologies, whereas others are unaware of their opportunities to take action. Main reason for that, as identified by the European Commission, is the lack of available and comparable vehicle energy consumption information of new technologies [5]. Others identified incremental costs as a major barrier to alternative commercial vehicle technology purchase [6]. In order to enable a reproducible and comparable assessment of various commercial vehicle concepts relating to individual transport applications, a holistic techno-economic evaluation approach for the assessment of future commercial vehicle concepts coping with the complexity of the road freight transportation sector was developed and implemented within a transport application based cost model named TACMO [7]. For detailed evaluation of the Total Cost of Ownership (TCO), expenditures for Maintenance & Repair (M&R) and the residual value are important to consider and should not be neglected [8]. However, previous TCO analyses of alternative commercial vehicle powertrain technologies used either existing values from conventional diesel technology or adapted values in any order based on own assumptions or expert guesses [9], [10], [11], [12]. Others exclude costs of M&R and resale value developments or using cost values determined for passenger cars [13], [14]. Basically, there is a lack of information and consolidated knowledge regarding the costs of M&R for alternative commercial vehicle powertrain technologies. The same applies for the residual value.

The objective of this paper is to introduce a comprehensive calculation methodology to quantify specific costs for Maintenance & Repair for different alternative commercial vehicle powertrain technologies in order to enable a holistic cost assessment for commercial vehicles. Further aim is to present an approach in order to assess the residual value for different alternative commercial vehicle powertrain technologies.

2 Methodology

2.1 Maintenance & Repair cost calculation

Costs for Maintenance & Repair include actions in order to decelerate the degeneration of parts (maintenance), to restore the functionality (repair) and to examine the current status of the vehicle (inspection). Six different vehicle sizes classified into vehicles with a cross vehicle weight (GVW) of 3.5 ton (transporter), 7.5 ton (rigid truck), 12 ton (rigid truck), 18 ton (rigid truck), 26 ton (rigid truck) and 40 ton (tractor-trailer) are taken into account. In addition, five different drivetrain architectures have been examined:

1) Conventional internal combustion engine vehicles (ICE) powered with diesel (D) as compressed ignition (CI) engine and powered with natural gas (NG) as spark ignition (SI) engine.
2) Parallel hybrid electric vehicles (HEV) with different functionalities and battery sizes: Mild hybrid (MHEV), full hybrid (FHEV) and plug-in hybrid (PHEV).
3) Serial hybrid electric vehicle with a range extender (REEV).
4) Battery electric vehicle (BEV)
5) Fuel cell electric vehicle (FCEV)

Based on mean time between failures (MTBF) or rather mean distance between failures (MDBF) replacements, costs as well as required labour input for the maintenance of 46 components and if required the replacement of 24 components are considered. In addition, costs for the different vehicle inspections like general inspection, safety inspection, exhaust emission test, leak test and pressure test of compressed gas storage systems are considered. The vehicles are defined by the type of powertrain (ICE-D/NG, MHEV-D/NG, FHEV-D/NG, PHEV-D/NG, BEV, REEV-D/NG/FC and FCEV) and the vehicle size (3.5 ton GVW, 7.5 ton GVW, 12 ton GVW, 18 ton GVW, 26 ton GVW, 40 ton GVW). Additionally and for the alternative powertrain types, the battery size, the vehicle range, the power level of the energy converters used and required power electronics, the share of driving in charge sustaining (CS) mode, the share of driving in charge depleting (CD) mode, and recuperative braking are taken into account for the cost calculation. The costs are calculated on a EUR per km level.

The costs for Maintenance & Repair per kilometre are the monetary sum of the total efforts for maintenance, repair and inspections over the vehicles total mileage (Equation. 1).

$$C_{i,j}^{\mathrm{M\&R}} = C_{i,j}^{\mathrm{M}} + C_{i,j}^{\mathrm{R}} + C_{i,j}^{\mathrm{I}} \tag{1}$$

Maintenance cost $C_{i,j}^{\mathrm{M}}$ per vehicle category i and powertrain type j correspond to the total sum of all costs over the vehicles total mileage $M_{i,j}^{\mathrm{total}}$ required for maintaining the powertrain components. The costs for maintenance depending on the frequency $f_{i,j,c}^{\mathrm{M}}$ to maintain an individual component and the related costs required for material usage $C_{i,j}^{\mathrm{material}}$ and labour $C_{i,j}^{\mathrm{labour}}$ (Equation 2). The labour costs are calculated as the product of the time it takes to maintain or replace the component and the hourly rate of the qualified personnel.

$$C_{i,j}^{\mathrm{M}} = \frac{\sum_{c=1}^{46} f_{i,j,c}^{\mathrm{M}} \cdot \left(C_{i,j,c}^{\mathrm{material}} + C_{i,j,c}^{\mathrm{labour}}\right)}{M_{i,j}^{\mathrm{total}}} \tag{2}$$

The maintenance frequency is determined based on year- and mileage-dependent service interval specifications. The maximum required maintenance frequency is used for the calculation. Relevant input data regarding powertrain dependent maintenance procedures and duration, component specific service intervals and cost for material usage are based on literature review and expert consultations. For REEV engine downsizing is considered. For MHEV, FHEV and PHEV it is assumed that the conventional powertrain is supplemented by the components of electrification. The maintenance procedures per component depending on vehicle category as well as powertrain type and categorized according to internal combustion engine, exhaust system, drive train, brake system, compressed air system, chassis, natural gas system, electrification, hydrogen system and other. An overview of the components and maintenance procedures considered is attached to the appendix (Table A.1 and Table A.2).

Costs for repair $C_{i,j}^{\mathrm{R}}$ per vehicle category i and powertrain type j correspond to the total sum of all costs over the vehicles total mileage required for restoring the functionality of the powertrain components and depending on the frequency $f_{i,j,c}^{\mathrm{R}}$ of necessary replacements of an individual component, the component replacement cost $C_{i,j}^{\mathrm{material}}$ and labour cost (Equation 3).

$$C_{i,j}^{\mathrm{R}} = \frac{\sum_{c=1}^{24} f_{i,j,c}^{\mathrm{R}} \cdot \left(C_{i,j,c}^{\mathrm{material}} + C_{i,j,c}^{\mathrm{labour}}\right)}{M_{i,j}^{\mathrm{total}}} \tag{3}$$

The replacement frequency of a component is determined based on its specific MDBF or MTBF. The MDBF/MTBF specifies the average distance/time between inherent failures of a system or component [15]. Regarding the components of conventional powertrains (ICE-D and ICE-NG) as well as the tires, MDBF/MTBF data is based on literature review, e.g. [16] and expert consultations. Corresponding to the UN/ECE Regulation No 110 a minimum service life of 15,000 refuelling operations is assumed for the natural gas storage system [17]. The batteries of MHEV, FHEV and FCEV are typically operated in micro cycles by a certain State of Charge (SOC) value. Therefore, the service life expectancy of these micro cycles on the battery system is expected to be marginal [18]. For this reason is the replacement of the battery system for hybridized powertrains assumed to be independent of the mileage driven. However, manufacturers grant eight-years of warranty on the battery system [19], [20], [21], [22]. In analogy to [18] and due to a reduction of the mechanical brake wear based on the functionalities stop-start and regenerative breaking, a hybridization factor η_{HF} is introduced which increases the MDBF of the braking system (Equation 4). The hybridization factor indicates the energy efficiency gains due to hybridization. It is ≥ 1 and varies depending on the vehicle size, the configuration of the electric machine, the underlying driving profile and operating strategy.

$$\mathrm{MDBF}_{i,j,c}^{*} = \mathrm{MDBF}_{i,j,c} \cdot \frac{1}{\eta_{\mathrm{HF}}} \tag{4}$$

The same applies for the MDBF of the internal combustion engine regarding FHEV, PHEV and REEV as a function of the charge sustaining (CS) driving-mode share $\eta_{\text{CS-mode}}$[1] (Equation 5).

$$\text{MDBF}^{*}_{i,j,c} = \text{MDBF}_{i,j,c} \cdot \frac{1}{\eta_{\text{CS-mode}}} \tag{5}$$

For vehicles with the functionality of purely electric driving, it is assumed that these are operated in the charge depleting (CD) mode from the beginning of the journey until the minimum state of charge is reached [23]. The cyclical number of the battery system is thus determined by the ratio of the total electrical driving share in kilometres and the electrical range of a vehicle concept. The cyclical number (full-load cycles) of lithium-nickel-manganese-cobalt oxides (NMC) battery technology is assumed to be 3,100 [32]. The MTBF of the power electronic and the electrical machine is assumed to be 10,000 operating hours [24]. Same applies for the fuel cell systems service life [25]. The actual operating hours are determined by the ratio of the total mileage and the average velocity of the underlying driving profile. A minimum service life of 5,000 refuelling operations is assumed for the hydrogen storage system. An overview of the components taken into consideration for repairs is attached to the appendix (Table A.3).

According to the German Road Traffic Licensing Regulations, vehicle owners are committed to have their vehicles inspected at regular intervals. Via the general inspection and the safety inspection the safety of the transport equipment is ensured. The environmental compatibility is checked by exhaust emission test. For vehicles with compressed gas storage systems regular leak tests and pressure tests have to be done. Therefore, the costs of inspections are the sum of the expenditures $C^{\text{I}}_{i,j}$ regarding the checks named above depending on the individual intervals $I_{i,j}$ expressed in months and the Service life h expressed in years (Equation 6).

$$C^{\text{I}}_{i,j} = \frac{a^{\text{GI}} \cdot C^{\text{GI}} + a^{\text{SI}} \cdot C^{\text{SI}} + a^{\text{ET}} \cdot C^{\text{ET}} + a^{\text{LT}} \cdot C^{\text{LT}} + a^{\text{PT}} \cdot C^{\text{PT}}}{M^{\text{total}}_{i,j}}$$
$$\textit{with}\ a^{\text{GI}} = \left\lfloor \frac{h \cdot 12}{I^{\text{GI}}_{i,j}} \right\rfloor, a^{\text{SI}} = \left\lfloor \frac{h \cdot 12}{I^{\text{SI}}_{i,j}} \right\rfloor, a^{\text{ET}} = \left\lfloor \frac{h \cdot 12}{I^{\text{ET}}_{i,j}} \right\rfloor, a^{\text{LT}} = \left\lfloor \frac{h \cdot 12}{I^{\text{LT}}_{i,j}} \right\rfloor, a^{\text{PT}} = \left\lfloor \frac{h \cdot 12}{I^{\text{PT}}_{i,j}} \right\rfloor \tag{6}$$

2.2 Assessment of the resale value

The residual value of a vehicle corresponds to the achievable selling price minus dismantling and disposal costs. A comprehensive analysis of residual values for alternative commercial vehicles is missing and data on this issue is rare. For this reason a multi-criteria assessment approach was developed taking into account a variety of input parameters such as the vehicle category and related gross vehicle weight, the type of powertrain, the purchase price of the vehicle, the vehicles total mileage, the infrastructure density and the technology maturity.

Via regression analyses based on real market data of the “Deutsche Automobil Treuhand GmbH” (DAT) [33] the functional relationship between the average initial purchase price of a vehicle and the average dealer selling price considering the total mileage of representative[2] vehicle models fulfilling the Euro VI emission standard was analysed. Due to commercial vehicles are investment assets for the provision of services it is assumed, that the impairment of value is highly affected by the kilometres driven. Therefore, the age of the vehicle is assumed to be insignificant. However, the age of the vehicle is implicit considered because the total mileage simplified represents the product of a certain service life[3] and an average yearly mileage.

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[1] CS driving-mode share with regard to the total mileage. The following applies: $\eta_{\text{CS-mode}} + \eta_{\text{CD-mode}} = 1$

[2] The representative vehicle models cover the models of the first three manufacturers with the highest number of new registrations.

[3] Only new registrations are considered. Therefore, the service life corresponds to the age of the vehicle.

Since mathematical-statistical data on the value losses of alternative commercial powertrain technologies is missing, this is determined on the basis of the result regarding the impairment in value of the representative vehicle models and by the use of fuzzy logic. Formally, the residual value of vehicle concepts $RV_{i,j}^{\mathrm{V}}$ can be determined as an exponential function considering the vehicles initial purchase price $IPP_{i,j}^{\mathrm{V}}$, the total mileage and the level parameters $a_{i,j}$ and $b_{i,j}$ (Equation 7).

$$RV_{i,j}^{\mathrm{V}} = IPP_{i,j}^{\mathrm{V}} \cdot a_{i,j} \cdot e^{\left(\frac{b_{i,j}}{\varepsilon_{i,j}} \cdot M_{i,j}^{\mathrm{total}}\right)} \tag{7}$$

The type of function and level parameters are determined on the basis of the DAT data set (see section 3.2). In order to take account of vehicles with alternative powertrain types in addition to conventional vehicle concepts, a scaling factor $\varepsilon_{i,j}$ is introduced[4]. Basically, an exponential development of the impairment of value is assumed which adapts to the development function of the representative vehicles, if the scale factor rises. The scale factor is determined by means of the fuzzy logic. Fuzzy logic is used for the depiction of vagueness and uncertainty if no mathematically-statistically data is available [27]. Based on verbal descriptions (heuristic interferenz rules) of a situation, fuzzy logic enables for a quantification of this. The determination of the scaling factor is based on two fuzzy variables which are justified by the following hypotheses:

- *Infrastructure density:* On the one hand, the infrastructure density describes the network coverage of installed charging and refuelling units. On the other hand, this includes the availability of spare parts and thus the size of the aftermarket. If both factors are small, it is to be expected that potential buyers are not willing to pay a resale value for alternative powertrains equivalent to the conventional powertrain. It follows that: the lower the infrastructure density, the lower the resale value to be achieved. The basic set of the fuzzy variable infrastructure density is the interval [0,1]. The range expresses a degree of fulfilment. A value close to one indicates a high infrastructure density.

- *Technology maturity:* The maturity of a technology is seen as an indicator of the current performance in terms of the development status of a technology. For example, for emerging technologies the dynamic of development is expected to be high, which results in a dynamic improvement of the technology performance. Consequently, short technology development cycles and rapid aging processes occur, which can be expected to lower the residual value. The basic set of the fuzzy variable technology maturity is the interval [0,1]. A value close to one indicates a high technology maturity level.

The fuzzy variables comprise a number of terms which are expressed in a first step as linguistic variables (fuzzification) and defined by a membership function. For the variable technology maturity the chosen linguistic terms[5] are: pacemaker technology, key technology and basic technology. For the variable infrastructure density the chosen linguistic terms are: very low, low, medium, high and very high. In a second step (inference), the input parameters are concatenated in the form of if-then relationships based on the interferenz rules and transferred to an output fuzzy set. In a third step, the determined output fuzzy set is converted into the quantitative scaling factor (defuzzification).

3 Results

Basically, the M&R cost model and the approach to assess the resale value can be applied on different vehicle types. The parameter sets were defined for six different vehicle types with different gross vehicle weights: 3.5 ton (transporter), 7.5 ton (rigid truck), 12 ton (rigid truck), 18 ton (rigid truck), 26 ton (rigid truck) and 40 ton (tractor-trailer). The powertrain technologies considered are ICE-D/NG, MHEV-D/NG, FHEV-D/NG, PHEV-D/NG, BEV, REEV-D/NG/FC and FCEV.

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[4] For the powertrain type ICE-D applies: $b_{i,j} = 1$

[5] In the literature linguistic terms are also referred as fuzzy sets. Fuzzy sets indicate the corresponding degree of fulfilment of a fuzzy logic statement for each numerically sharp value of an input parameter [28].

In the European Union, long-haul tractor trailers are the largest sales category of heavy-duty vehicles (HDVs) and the largest emitter of CO_2 emissions [29]. Therefore, for the illustration and discussion of the results a tractor-trailer combination with a gross vehicle weight of 40 ton and a 4x2 drivetrain is chosen. Additionally, and in order to represent the other end of the wide spectrum of trucks for freight delivery applications, a rigid truck for urban operation with a gross vehicle weight of 12 ton is considered.

The results shown within the following section 3.1 and section 3.2 are based on the general input parameter set as shown in Table 1 and Table 2.

Table 1: Definition of vehicle parameters for a long haul tractor-trailer with a gross vehicle weight of 40 ton

Parameter	Unit	ICE-D	MHEV-D	PHEV-D	ICE-LNG	BEV	FCEV
ICE power max.	kW	335	335	335	335	-	-
ICE torque max.	Nm	2,200	2,200	2,200	2,200	2,200	2,200
Storage capacity diesel	l	400	400	400	-	-	-
Storage capacity natural gas	kg	-	-	-	180	-	-
Storage capacity hydrogen	kg	-	-	-	-	-	90
Power of fuel cell system	kW_{el}	-	-	-	-	-	92 [e]
Power of EM & PE	kW_{el}	-	60	335	-	335	335
Usable energy content of the battery system	kWh	-	5	30	-	700	5
Total range [a]	km	1,184	1,229	1,368	632	-	1,113
Electric only range [a]	km	-	-	19	-	429	-
η_{HF} [b]	-	-	1.05	1.13	-	-	1.13
$\eta_{\mathrm{CS-mode}}$	-	1	1	0.93	1	-	1
Average yearly mileage [c]	km	100,000	100,000	100,000	100,000	100,000	100,000
Service life [d]	years	5	5	5	5	5	5
Initial purchase price at medium yearly production units [f]	€$_{2010}$	152,140	164,577	172,916	168,046	549,512	229,324

[a] payload of 17,315 kg - WHVC highway cycle; [b] regarding WHVC highway cycle;[c] according to [30]; [d] according to [31]; [e] the power of the fuel cell system corresponds to the average power needed for the WHVC cycle; [f] production units >10,0000 – 100,000; results of the Transport Application based Cost Model (TACMO) [7]

Table 2: Definition of vehicle parameters for an urban delivery rigid truck with a gross vehicle weight of 12 ton

Parameter	Unit	ICE-D	MHEV-D	PHEV-D	ICE-CNG	BEV	FCEV
ICE power max.	kW	169	169	169	169	-	-
ICE torque max.	Nm	875	875	875	875	875	875
Storage capacity diesel	l	120	120	120	-	-	-
Storage capacity natural gas	kg	-	-	-	60	-	-
Storage capacity hydrogen	kg	-	-	-	-	-	9
Power of fuel cell system	kW_{el}	-	-	-	-	-	40 [e]
Power of EM & PE	kW_{el}	-	40	169	-	169	169
Usable energy content of the battery system	kWh	-	3	20	-	150	3
Total range [a]	km	569	698	842	329	-	239
Electric only range [a]	km	-	-	25	-	197	-
η_{HF} [b]	-	-	1.22	1.44	-	-	1.37
$\eta_{\mathrm{CS-mode}}$	-	1	1	0.77	1	-	1
Average yearly mileage [c]	km	39,000	39,000	39,000	39,000	39,000	39,000
Service life [d]	years	5	5	5	5	5	5
Initial purchase price at medium yearly production units [f]	$€_{2010}$	69,675	77,671	88,931	74,109	169,032	80,655

[a] payload of 3,289 kg - WHVC urban cycle; [b] regarding WHVC urban cycle;[c] according to [30]; [d] according to [31]; [e] the power of the fuel cell system corresponds to the average power needed for the WHVC cycle; [f] production units >10,0000 – 100,000; results of the Transport Application based Cost Model (TACMO) [7]

3.1 Maintenance and repair cost for commercial vehicles with different powertrain technologies

The M&R cost comparison for different powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton shows that for all of the considered alternative powertrains MHEV-D, PHEV-D, ICE-LNG, BEV and FCEV are estimated to have lower costs (see Table 3). The hybrid powertrains mainly benefit from reduced wear and tear of the brake system. Lower usage of the combustion engine are compensated by expenses for the electrified drivetrain. The cost reduction under the given framework is expected to be 2 % for the MHEV-D and the PHEV-D powertrain type. For the ICE-LNG powertrain, the cost reduction is expected to be 3 %, mainly due to a less complex exhaust system. By a highly electrified powertrain, which is the case for the BEV, significantly lower costs of about 33 % are expected in case no replacement of the battery system, electric machine and the power electronic are required. Same applies for the FCEV powertrain with expected lower costs of about 30 %. Compared to the BEV powertrain, the hydrogen system requires higher maintenance expentidures.

Table 3: Total M&R cost comparison for different powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton

M&R	unit	ICE-D	MHEV-D	PHEV-D	ICE-LNG	BEV	FCEV
total cost	EUR_{2010}	73,291	71,961	71,746	71,387	49,064	51,387
cost per km [b]	EUR_{2010}/km	0.147	0.144	0.143	0.143	0.098	0.103
difference [a]	%	ref.	- 2 %	- 2 %	- 3 %	- 33 %	- 30 %

[a] relative cost compared to ICE-D; [b] cost for the trailer are 0,021 EUR/km and based on the average costs for an curtainsider (3-axle) given in [16]; the values calculated for the ICE-D tractor are in the range given in [16]

Figure 1 illustrates the maintenance, repair and inspection cost differences for various powertrain types of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton.

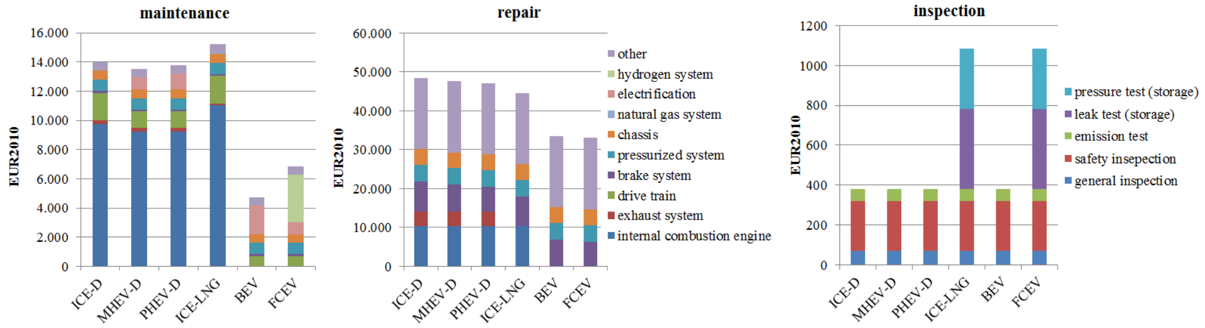

Figure 1: Maintenance, repair and inspection total cost comparison for different alternative powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton

Looking at M&R costs for different powertrain technologies of a rigid truck in urban operation with a gross vehicle weight of 12 ton, a cost reduction of about 4 % is expected for the MHEV-D. A cost reduction of 2 % is expected for the PHEV-D. Higher maintenance cost of the electrification compared to the MHEV-D cannot be compensated through reduced wear and tear of the brake system. For the average yearly mileage chosen, brake system repair costs of the PHEV-D equals them of the MHEV-D. For the ICE-CNG higher costs of about 4 % are expected. The additional costs regarding the spark ignition engine cannot be compensated by the benefits of the simplified exhaust system. For the BEV a cost reduction of 45 % and for the FCEV a cost reduction of 32 % is expected (see Table 4).

Table 4: Total M&R cost comparison for different powertrain technologies of a rigid truck in urban operation with a gross vehicle weight of 12 ton

M&R	unit	ICE-D	MHEV-D	PHEV-D	ICE-CNG	BEV	FCEV
total cost	EUR_{2010}	20,017	19,287	19,562	20,792	11,007	13,619
cost per km [b]	EUR_{2010}/km	0,103	0,099	0,100	0,107	0,056	0,070
difference [a]	%	ref.	- 4 %	- 2 %	+ 4 %	- 45 %	- 32 %

[a] relative cost compared to ICE-D; [b] the values calculated for the ICE-D rigid truck are in the range given in [16]

Figure 2 illustrates the maintenance, repair and inspection cost differences for various alternative powertrain technologies of a rigid truck in urban operation with a gross vehicle weight of 12 ton.

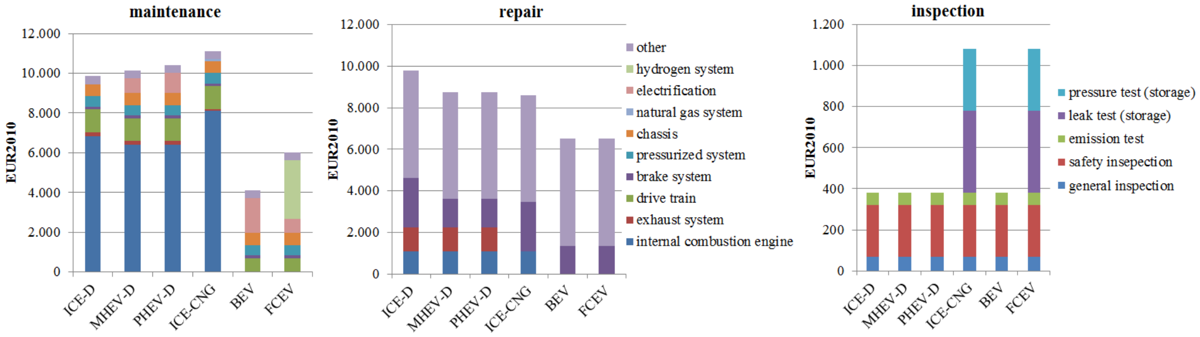

Figure 2: Maintenance, repair and inspection total cost comparison for different alternative powertrain technologies of a rigid truck in urban operation with a gross vehicle weight of 12 ton

3.2 Resale values for commercial vehicles with different powertrain technologies

The results of the regression analyses based on the DAT data set are shown within Figure 3. The corresponding function parameters are included in Table 5. The highest coefficient of determination was reached by the use of an exponential regression function. The result indicates that the impairment of value in percentage depending on the vehicle category and the gross vehicle weight. With an increase in the gross vehicle weight, the impairment of value over the total mileage is less which results in a slight curvature of the regression function. For rigid trucks of the vehicle category N_3 with a total gross vehicle weight of 26 ton, the impairment in value is also dependent on the application profile and required vehicle configuration. For example, if the truck is equipped with a long distance driving cab (N_3: 26 t GVW (2)), the development of the impairment value approaches that of the tractor[6].

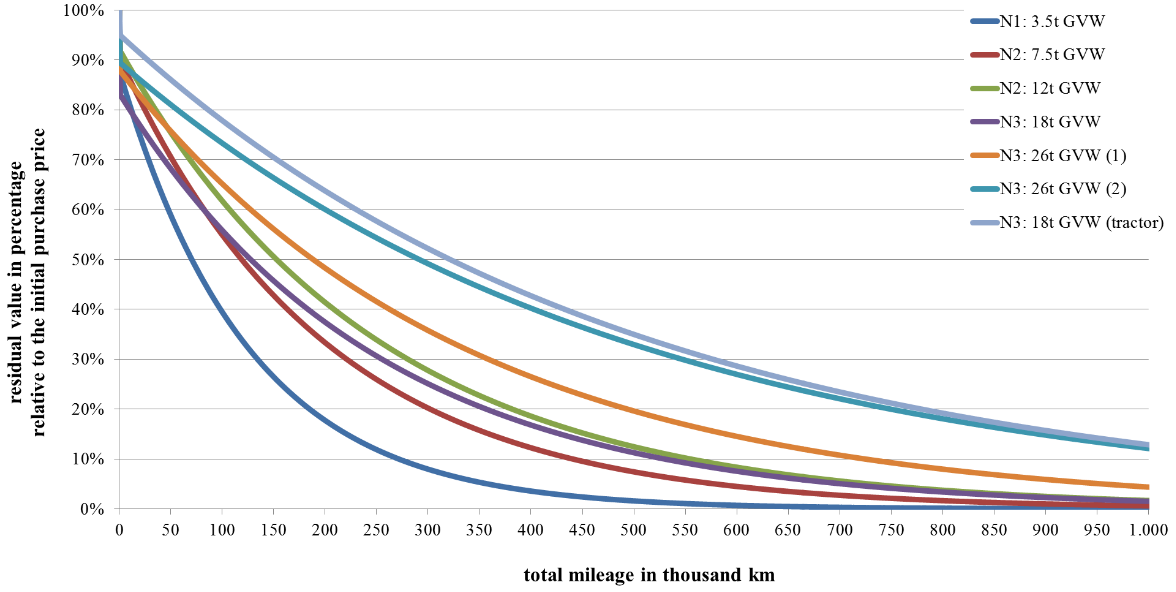

Figure 3: Development of the residual value in percentage relative to the initial purchase price of the representative vehicle models

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[6] As data for the development of the resale value for trailers is not available and due to the price of it compared to the trailer is low it is neglected. Only the tractor is considered.

Table 5: Parameters of the exponential regression function regarding the residual value development of the representative vehicle models

	parameters of the exponential regression function: $f(x)=a\cdot\exp(b\cdot x)$		
vehicle category & GVW	a	b	R^2
N_1: 3.5 t	8.79E-01	-8.00E-03	0.94
N_2: 7.5 t	9.06E-01	-5.00E-03	0.98
N_2: 12 t	9.22E-01	-4.00E-03	0.99
N_3: 18 t	8.33E-01	-4.00E-03	0.95
N_3: 26 t (1)	8.80E-01	-3.00E-03	0.96
N_3: 26 t (2)	8.96E-01	-2.00E-03	0.98
N_3: 18 t (tractor)	9.51E-01	-2.00E-03	0.99

Table 6 includes the definition of the fuzzy variables infrastructure density and technology maturity according to the various powertrain types considered. The parameter setting was done from the current point of view compared to the leading powertrain technology ICE-D.

Table 6: Definition of the fuzzy variables infrastructure density and technology maturity according to the various powertrain types considered

	ICE-D	MHEV-D	PHEV-D	ICE-CNG/ LNG	BEV	FCEV
Infrastructure density	very high	high	medium	low/ very low	medium	very low
Technology maturity	basic	key	pacemaker	key/key	pacemaker	pacemaker

The assessment of the resale value for different alternative powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton and of a rigid truck in urban operation with a gross vehicle weight of 12 ton bases on the approach described in 2.2. The results are shown within Table 7 and Table 8. For the tractor-trailer in long-haulage operation powered by the ICE-D powertrain, the resale value accounts for 35 % of the initial purchase price. For the MHEV-D the resale value accounts for 23 % of the initial purchase price. The resale values of the PHEV-D, ICE-LNG and BEV accounts for 3 % of the initial purchase price. For the BEV it is assumed, that there is no need for the use of public charging infrastructure. The vehicles charging only once a day overnight at the depot. However, there is no aftermarket which is the reason for the assumption of a medium infrastructure density. Due to the very low infrastructure density and the assumed pacemaker technology maturity, no resale value for the FCEV is expected.

Table 7: Resale values for different alternative powertrain technologies of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton

		ICE-D	MHEV-D	PHEV-D	ICE-LNG	BEV	FCEV
Resale value	EUR_{2010}	53,243	37,520	5,868	5,703	18,649	0
Relative to the initial purchase price	%	35	23	3	3	3	0

The resale value for the powertrain type ICE-D regarding the rigid truck in urban operation accounts for 42 % of the initial purchase price. For the MEHV-D the resale value account for 30 % and for the PHEV-D, ICE-CNG as well as BEV it accounts for 7 % of the initial purchase price. No resale value is expected for the FCEV.

Table 8: Resale values for different alternative powertrain technologies of a rigid truck in urban operation with a gross vehicle weight of 12 ton

		ICE-D	MHEV-D	PHEV-D	ICE-CNG	BEV	FCEV
Resale value	EUR_{2010}	29,435	23,489	6,087	5,073	11,570	0
Relative to the initial purchase price	%	42	30	7	7	7	0

4 Conclusions

A methodology to quantify specific costs for Maintenance & Repair for different alternative commercial vehicle powertrain technologies was introduced. Based on a bottom-up approach, 46 individually assessed components regarding maintenance and 24 individually assessed components regarding repair as well as different inspections were considered. The parameter sets were defined for six different vehicle types with different gross vehicle weights: 3.5 ton (transporter), 7.5 ton (rigid truck), 12 ton (rigid truck), 18 ton (rigid truck), 26 ton (rigid truck) and 40 ton (tractor-trailer). The powertrain technologies considered are ICE-D/NG, MHEV-D/NG, FHEV-D/NG, PHEV-D/NG, BEV, REEV-D/NG/FC and FCEV. Basically, for the electrified powertrains lower M&R costs are expected. However, in case major powertrain components have to be replaced, the benefits of the electrification are expected to be overcompensated. In addition to the methodology to quantify specific costs for Maintenance & Repair, an approach in order to assess the residual value for different alternative commercial vehicle powertrain technologies was presented. Therefore, it was assumed that the resale value of alternative commercial vehicle powertrains show faster depreciation rates depending on the infrastructure density and the technology maturity. Exemplary results are presented for the different powertrain technologies ICE-D, MHEV-D, PHEV-D, ICE-NG, BEV and FCEV of a tractor-trailer in long-haulage operation with a gross vehicle weight of 40 ton and a rigid truck in urban operation with a gross vehicle weight of 12 ton. Altogether, by the use of the M&R methodology and the resale value approach, required data in order to enable a holistic cost assessment for commercial vehicles can be provided.

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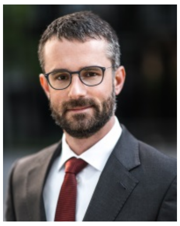

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Appendix

Table A.1: Maintenance procedures - Part 1

Component	Step
Internal combustion engine	
Starter battery	Performance test and contact lubricant
Dynamo	Replacement of carbon brushes
Starter	Replacement of carbon brushes
Cylinder head	Replacement of gasket
Fan belt	Replace
Cam belt	Replace
Air filter	Replace
Fuel filter	Replace
Oil filter	Replace
Engine oil	Replace
Cooling fluid	Check and refill
Valve	Check and adjust valve clearances
Spark plug	Replace
Exhaust system	
Exhaust system	Visual inspection on oxidation
SCR system	Check and refill
Drive train	
Transmission oil	Replace
Clutch	Check and adjust
Brake system	
Brake pad	Visual inspection
Brake disc	Visual inspection
Brake-hose	Visual inspection
Brake fluid	Replace
Braking force compensator (ABL)	Visual inspection
Compressed air system	
Squeezer	Visual inspection
Air drier cartridge	Replace
Pressure tank	Visual inspection
Air pipe & clutch	Visual inspection

Table A.2: Maintenance procedures - Part 2

Component	Step
Chassis	
Shock absorber	Visual inspection
Spring	Visual inspection
Wheel bearing	Visual inspection
Articulated joint	Visual inspection
Air bellows	Visual inspection
Natural gas system	
Storage system	Visual inspection
Electrification	
High-voltage battery system	Performance and visual inspection
Electric machine	Visual inspection
Power electronics	Visual inspection
Coolant	Check and refill
Dryer cartridge	Replace
Hydrogen system	
Air filter (cathode)	Replace
Hydrogen sensor system	Performance test
Vent hole	Visual inspection
Blow-off line	Visual inspection
Ion exchanger	Replace
Coolant	Check and refill
Storage system	Visual inspection
Other	
Hydraulic oil (steering)	Check and refill
Tires	Check on wear and tear and air pressure

Table A.3: Components taken into consideration for repairs

Component	Step
Internal combustion engine	
Starter battery	Replace
Water pump/ radiator	Replace
Turbocharger	Replace
Exhaust system	
Exhaust system	Replace
Particle filter	Replace
SCR system	Replace
Drive train	
Gearbox	Replace
Clutch	Replace
Drive shaft	Replace
Brake system	
Brake pad	Replace
Brake disc	Replace
Compressed air system	
Squeezer	Replace
Pressure tank	Replace
Pressure pipe and clutches	Replace
Chassis	
Shock absorber	Replace
Wheel bearing	Replace
Air bellows	Replace
Natural gas system	
Storage system	Replace
Electrification	
High-voltage battery system	Replace
Electric machine	Replace
Power electronics	Replace
Hydrogen system	
Fuel cell system	Replace
Storage system	Replace
Other	
Tires	Replace