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# Scenario analyses for the techno-economical evaluation of the market diffusion of future commercial vehicle concepts

Florian Kleiner[1,2], Horst E. Friedrich[1]

[1]*German Aerospace Center (DLR), Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*

[2]*Corresponding author, Florian.Kleiner@dlr.de*

**Summary**

The article presents a bottom-up approach to model the German road haulage market of new light and heavy commercial vehicle registrations with different gross vehicle weights and competing powertrain technologies considering different transport tasks. It allows for the analysis under which market conditions alternative powertrain technologies can enter the market and gain market shares. It was developed to especially support strategic decisions of policy makers, e.g. regarding the implementation of a $CO_2$ regulation framework for heavy commercial vehicles, and manufacturers, e.g. regarding the identification of future market potentials for alternative vehicle concepts, in order to face the challenge to reduce the emissions caused by road freight vehicles. Via a reference scenario, the new registrations of alternative powertrain technologies in the 2015 to 2040 timeframe is shown for the German road haulage market in total and separately for the light and heavy commercial vehicle market. The results display a retaining dominant market share of vehicle concepts using an internal combustion engine. However, due to the implementation and tightening of $CO_2$ regulations advanced powertrain technologies are required in order to meet the targets set and thus faster entering the market.

*Keywords: freight transport, market development, HEV (hybrid electric vehicle), EV (electric vehicle)*

## 1 Introduction

In Germany, the transport sector is the second largest consumer of final energy and accounts for about 29 % of the final energy consumption [1]. Road traffic dominates the share of the transport sectors final energy consumption with about 83 % [2]. While motorized individual and public road transport were able to reduce its energy consumption in the past, the energy consumption of road freight transport increased by about 20 % due to an increase in supply volume [2], [3]. According to forecasts, transport performance is expected to increase yearly by 1.7 % [4]. Over 94 % of the current commercial vehicle stock and commercial vehicle registrations are powered by diesel as fuel. Commercial vehicles with alternative powertrains account for about 1 % of the vehicle stock, dominated by natural gas technology mainly used by light commercial vehicles [5], [6]. The carbon dioxide ($CO_2$) emission share of commercial vehicles regarding the total $CO_2$-emissions of the road transport is about 20 %, although commercial vehicles represent 6 % of the total vehicle stock [7], [8]. However, due to existing market barriers regarding the purchase of alternative powered vehicles and not existing regulatory measures in order to monitor vehicle related $CO_2$-emissions of heavy commercial vehicles, a continuing increase of the road freight transport related $CO_2$-emissions can be expected. This would not be compatible to the target set within the transport white paper, to reduce road traffic related greenhouse gas (GHG) emissions by around 60 % compared to the level of 1990 in order to reach a competitive low carbon economy by 2050 [9]. Due to the leadership position of Germany within the European Union regarding the yearly sales figures and transport performance, particularly of heavy commercial vehicles, a contribution from Germany to the GHG-emission target set within the transport white paper would be highly significant [10]. Altogether, the challenge to cope with is to reduce not only road freight vehicle related $CO_2$ emissions, but also the $CO_2$ footprint of the energy used considering specific frameworks of the market.

The public and scientific discourse about how to face this challenge occurs, compared to the motorized individual road transport, only to a minor degree. On the one hand, several analyses focus on the fuel consumption reduction potential of individual technologies for conventional commercial vehicles powered by diesel as fuel [11] - [14]. On the other hand, present studies focus on total cost of ownership analyses, mainly on the cost comparison of conventional diesel, battery and fuel cell electric powertrain concepts [15] – [18]. Road haulage market analyses of the diffusion of alternative powertrain technologies are scarce. Two studies exist which focus on the German heavy commercial vehicle market. Both studies following a top-down modelling approach which is characterized by a highly aggregated consideration level [19], [20]. However, the road haulage market is highly diverse. Light and heavy commercial vehicles with differences in their gross vehicle weight operating in different transport tasks. Therefore, detailed transport task specific techno-economic analyses of vehicles with different gross vehicle weights and competing powertrain technologies is necessary and requires a bottom-up modelling approach. At the Institute of Vehicle Concepts of the German Aerospace Center, a novel model was developed in order to perform comprehensive scenario analyses of the total German road haulage market of new registrations considering competing powertrain technologies based on a bottom-up modelling approach.

The aim of the study is to introduce the developed modelling approach of the German road haulage market of new light and heavy commercial vehicle registrations with different gross vehicle weights and competing powertrain technologies considering different transport tasks. Therefore, the model approach will be explained in the second section of this article. Subsequently, the relevant scenario inputs are described. Key results including a sensitivity analysis based on a reference Scenario will be shown and discussed in the concluding sections.

# 2 Methodology

The presented road haulage vehicle technology market model based on a combined bottom-up, agent-based and discrete choice approach and assesses the competition between conventional and alternative powertrain technologies for light and heavy commercial vehicles. Via the model approach vehicle concepts, representing the supply side, and fleet operators, representing the demand side, by considering external influences and road haulage market behaviour characteristics are interlinked (Figure 1).

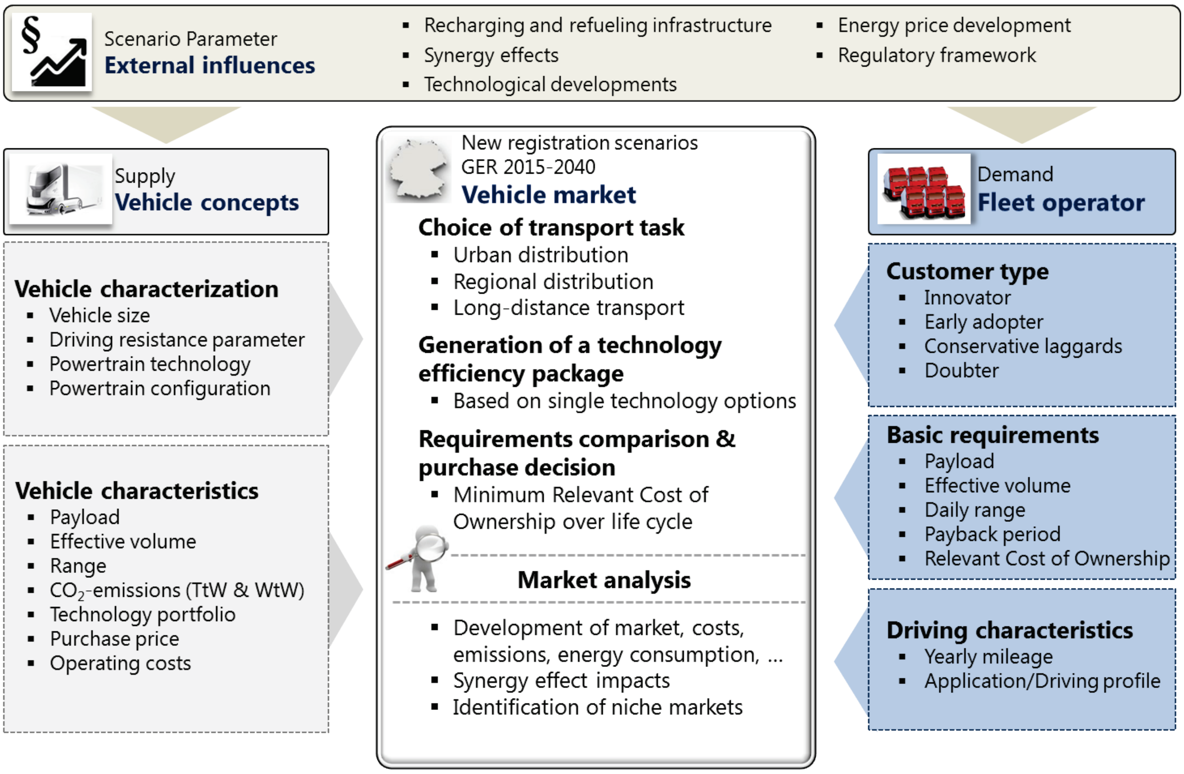


Figure 1: Approach of the road haulage vehicle technology market model

## 2.1 Vehicle concepts (Supply)

In principle, the supply is restricted to the commercial vehicle concepts available on the market. Therefore, baseline vehicles according to the state-of-the-art of a reference year were created which represents the average of the new registrations of an entire vehicle segment. As representative for the German road haulage market six different vehicle segments with different gross vehicle weights (GVW) and an internal combustion engine powertrain are taken into account. These are vehicles with a 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). The focus is set on vehicles for freight delivery applications with drive axel configurations of 4 x 2 and 6 x 2. Therefore, refuse hauling, construction, and dump trucks are not considered, all of which usually have a larger number of driven axles e.g. 6 x 4 or 6 x 6, larger engines, and larger payload capabilities. The vehicle characterization made, according to the different vehicle segments, based on a comprehensive literature research and comprises the definition of the driving resistance parameters like the vehicles mass, rolling resistance coefficient and air drag coefficient, and the configuration of key powertrain components. However, beside the conventional powertrain technology, alternative powertrain technologies are offered which are not available on the market yet in order to enable them to compete. For the scenario analyses, the vehicle supply, therefore, is not restricted to the available commercial vehicle concepts of the reference year. In addition, a limitation of the market supply of commercial vehicles with alternative powertrains is not considered. The different types of competing powertrain technologies considered regarding all vehicle segments are: Internal combustion engine powered with diesel (ICE-D) or natural gas (ICE-NG), parallel hybrids like mild hybrid (MHEV-D/NG), full hybrid (FHEV-D/NG) and plug-in hybrid (PHEV-D/NG), series hybrid with range extender (REEV-D/NG/FC), battery electric (BEV) and fuel cell electric (FCEV). Due to the insignificant market share of gasoline powertrains especially for heavy commercial vehicles, these powertrain concepts are neglected. In order to determine the individual vehicle characteristics like the payload, the usable volume, the range, the Tank-to-Wheel (TtW) and Well-to-Weel (WtW) $CO_2$-emissions, the purchase price and the operating costs, the four step bottom-up approach of the Transport Application based Cost Model named TACMO as described within [21] is used. In addition, for each vehicle segment and powertrain technology, a technology portfolio is provided, which is separated into the four different categories, powertrain, lightweight design, aerodynamic and other. It comprises various single technology options which further improve the vehicles efficiency.

## 2.2 Fleet operator (Demand)

Fleet operators, representing the demand, decide about either to purchase commercial vehicles with conventional or with alternative powertrains. In the sense of agent-based modelling with a discrete choice approach each individual agent stands for a purchase decision of a certain amount of vehicles. Therefore, these agents represent an individual fraction of the total market depending on the combination of four attributes. The first attribute is the payback period, which has a key influence on the purchase decision [11], [22]. Therefore, the innovativeness and willingness to purchase advanced vehicle technology is defined by a maximum required payback period. In this context, advanced vehicle technology can either be a set of single technology options for the further improvement of the baseline vehicle or it can be an alternative powertrain technology type. Four customer types with different maximum payback periods are distinguished based on the results of an empirical survey of German fleet operators in terms of their individual payback period requirements [23]. In addition, the size share in percentage of the four distinguished customer types is defined accordingly. The four customer types are named innovator, early adopter, conservative laggard and doubter. It is assumed that, the higher the maximum required payback period the more innovative is the fleet operator and the higher is his willingness to purchase advanced vehicle technology. The second attribute, vehicle segment, is set to match the six different vehicle segments according to historical data, mentioned within section 2.1. The transport task is the third attribute. Urban freight distribution, regional freight distribution and long-distance freight transport with the related transport task characteristics, as explained within [21], are considered. The fourth attribute is the annual mileage, which is depending on the transport task characteristics. For the 3.5 ton GVW segment, the transport survey data set "Kraftfahrzeugverkehr in Deutschland 2010" (KID 2010) [24] was used to derive probability distributions of the annual mileage. For the remaining vehicle segments, probability distributions of the annual mileage were determined based on a special analysis of statistical road freight transport data of the year 2014 performed by the German Federal Office for Motor Vehicles "Kraftfahrt-Bundesamt" (KBA). The special analysis shows the number of trips per route in kilometres depending on the vehicle segment. By the use of Monte Carlo simulation and additional assumptions regarding the average number of daily trips, probability distributions of the annual mileage were determined and calibrated to the statistical average yearly mileage data per vehicle segment, also provided by the KBA. In total, up to 772 different fleet operator agents are considered. In addition to the four attributes, the agents have basic vehicle requirements as to payload, usable volume and daily driving range.

## 2.3 External influences (Scenario Parameter)

External influences affecting the market analyses considered are the availability of recharging and refuelling infrastructure, synergy effects, technological developments, energy price development and the regulatory framework.

The density of recharging and refuelling infrastructure is considered to be affecting the impairment of value as described within [25]. Therefore, the influence of recharging and refuelling infrastructure on the market diffusion of alternative powertrain technologies is modelled indirect via the Relevant Cost of Ownership and not as a direct criterion for exclusion.

A dynamic market development of alternative powertrain technologies in the passenger car market is expected to influence the market development in the 3.5 ton GVW segment, due to similar power and dimensioning requirements, which might also result in an accelerated technology adoption. Indeed, for the remaining commercial vehicle segments the power level and dimensioning is different. However, the market development might be affected through the learning effects gained. This synergy effect is modelled by the consolidation of the accumulated production amounts reached in the different markets and, therefore, affects the technology cost development.

Via the technology portfolio, technological developments like efficiency improvements or improvements in the energy density of a single technology option are considered. The single technology options and the related costs are based in a comprehensive literature review and provided for each powertrain technology considered. The related efficiency potential is depending on the vehicle configuration and the transport task and was thus determined based on own calculations. The modelling approach used is for the determination of the efficiency potential is explained in [21].

The yearly price development of the energy carriers used is based on future expected fuel / energy production scenarios and considers the national fuel / energy tax regulations.

Beside the fuel and energy tax regulations, annual vehicle taxes, toll rates and incentives at vehicle purchase are considered. For a comprehensive overview of relevant regulations see [26]. In order to cope with the challenge mentioned, special attention is paid to $CO_2$ regulation, which is seen as a major driver of a vehicles fleet's technological development. A $CO_2$ regulation is implemented on a vehicle segment level and penalises the vehicles exceeding a given $CO_2$ target value. If a $CO_2$ target values is in place, which is the case for the 3.5 ton GVW segment, but not so for the remaining segments, the model is calibrated in that way to meet the exogenously given $CO_2$ target. This approach is based on the assumption that the OEMs ensure to meet the $CO_2$ targets in order to avoid penalty fees. For each vehicle exceeding the given $CO_2$ target value, a monetary penalty on the purchase price, depending on the exceedance of limit value is obligatory.

## 2.4 Vehicle market

As mentioned, the road haulage market is highly diverse. Light and heavy commercial vehicles with differences in their gross vehicle weight operating in different transport tasks. Therefore, for modelling the road haulage market of new registrations, typical transport tasks of road freight deliveries, urban freight distribution, regional freight distribution and long distance freight transport are differentiated. Depending on the transport task, an implemented algorithm generates fleet operator individual efficiency packages on the basis of the provided vehicle technology portfolio and taking account of the payback period requirements. The algorithm requires a ranking in terms of the transport task specific benefit of a technology option. This ranking is achieved through the application of the House of Technology (HOT) approach [27]. The purchase decision is modelled in a three-step process. First, fleet operators scan the market for available vehicles and exclude those that do not match their own requirements regarding payload, effective volume and daily range. In the second step, the remaining vehicles are rated according to their payback period and Relevant Cost of Ownership (RCO). The payback period $PP$ is the duration of time required to recover the cost of all vehicle related investments. Within this study the payback period in years is calculated by considering the difference in all vehicle related investment costs $\Delta I$ and the difference in all vehicle related operating costs $\Delta O$ a year of an alternative powertrain concept compared to the ICE –D reference vehicle (Equation 1).

$$PP = \frac{\Delta I}{\Delta O} \tag{1}$$

Beside the payback period, one of the most important criteria regarding the purchase decision are the Total Cost of Ownership (TCO) over service life [20]. However, as explained within [21], the term RCO is used in the following. RCO are calculated considering vehicle investment cost $I^{\mathrm{V}}$, vehicle yearly operating cost $O^{\mathrm{V}}$, the resale value $R^{\mathrm{V}}$ of the vehicle after service life $h$, possible tax advantages $T^{\mathrm{V}}$, monetary subsidies $S^{\mathrm{V,I}}$, investment cost $I^{\mathrm{I}}$ and yearly operating cost $O^{\mathrm{I}}$ of required private charging or fuelling equipment (Equation 2). The RCO represent the final capital value of an investment depending on an expected service life and the interest rate $z$.

$$RCO = (1+z)^h \cdot (I^{\mathrm{V}} + I^{\mathrm{I}} - S^{\mathrm{V,I}}) + \left(\frac{(1+z)^h - 1}{z}\right) \cdot (O^{\mathrm{V}} + O^{\mathrm{I}}) - R^{\mathrm{V}} - T^{\mathrm{V}} \tag{2}$$

Vehicle and infrastructure investment costs reduced by incentives given correspond to the amount a fleet operator has to pay when purchase a vehicle. Vehicle technology costs are calculated bottom-up to cover a technologically detailed cost development over time. The operating costs are calculated on a yearly basis. The operating costs of the vehicle consist of fixed and variable annual costs. Vehicle fix costs are vehicle tax, vehicle insurance and labour cost. Vehicle variable costs are energy consumption cost, cost for maintenance and repair as well as toll expenditures. The cost for maintenance and repair based on a bottom-up cost calculation and the assessment approach used in order to determine the resale value is explained in [25]. Yearly operating cost of the required infrastructure equipment is fix but depending on the required charging power. The tax advantage is calculated considering the company tax rate $s$, a linear depreciation of the vehicles purchase price, the vehicles yearly operating cost, the resale value and in case of a lower average service life $n$ compared to the actual service life $h$ a special depreciation amount (Equation 3). Basically, it is assumed that the profit of the fleet operators is sufficient high enough.

$$T^{\mathrm{V}} = \left[\left[\left(\left(\frac{I^{\mathrm{V}} - S}{n}\right) + O^{\mathrm{V}}\right) \cdot \left(\frac{(1+z)^{h} - 1}{z}\right)\right] + (I^{\mathrm{V}} - R^{\mathrm{V}} - S) \cdot \left(1 - \frac{h}{n}\right)\right] \cdot s \tag{3}$$

In contrast to the adoption behavior of private consumer, the organizational adoption behavior is highly rational [20]. As mentioned, the costs of ownership over service life are, beside the payback period, one of the most important criteria regarding the purchase decision. Therefore, the fleet operator decides in the final third step for the vehicle concept with the minimum RCO over service life. The RCO calculation and the purchase decision are carried out annually from 2015 to 2040 for each vehicle concept of a vehicle segment and separately for all transport tasks considered. As a result, the market share of a vehicle concept is illustrated. The market share of a vehicle concept corresponds to the ratio of the sales numbers of a vehicle concept and the number of vehicles available. The market share is determined for each year and can be differentiated on three levels. Transport task specific market share per vehicle segment, total vehicle segment specific market share as well as total light and heavy commercial vehicle market share. In order to include improvements in the manufacturing process gained with increasing production numbers, experience curves are used to endogenously calculate the future technology costs of key alternative powertrain components (Equation 4). Relevant inputs are the initial production cost $C_0$ and related initial cumulated production amount $P_0$. The learning rate $r$, expresses the factor by which the production cost decease when the production scale doubles. Hence, $C(P)$ corresponds to the cost of production at the cumulated amount $P$ of a technology.

$$C(P) = C_0 \cdot \left(\frac{P}{P_0}\right)^{\frac{\ln(r)}{\ln(2)}} \tag{4}$$

By default, only the sales development of the light and heavy commercial vehicle market in one year trigger the sales in later years, as cost decrease when cumulated sales increase. If synergy effects, as explained in section 2.3, are considered, the cumulated sales of the additional market are added to the ones of the light and heavy commercial vehicle market. The total cumulated vehicle sales of both markets serve than as input for the experience curve.

# 3 Key assumptions and data

For the techno-economical evaluation of the market diffusion of future commercial vehicle concepts a reference scenario is calculated based on the described modelling approach. The reference scenario reflects an extrapolation of today's situation and considers a moderate development of existing technological and political trends. Synergy effects are not considered. The crude oil price increases moderately. Fuel, gas and electricity prices do not experience strong changes in their taxation schemes (Table 1).

Table 1: Fuel and energy price developments considered

| Parameter | Unit | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|---|---|
| Diesel price [a] | $EUR_{2010}$/l | 0.91 | 0.96 | 1.15 | 1.20 | 1.25 | 1.30 |
| CNG price [b] | $EUR_{2010}$/kg | 0.92 | 0.95 | 0.96 | 0.98 | 0.99 | 1.01 |
| LNG price [c] | $EUR_{2010}$/kg | 1.03 | 1.07 | 1.08 | 1.10 | 1.11 | 1.13 |
| Electricity price [d] | $EUR_{2010}$/kWh | 0.21 | 0.23 | 0.25 | 0.22 | 0.22 | 0.21 |
| Hydrogen price [e] | $EUR_{2010}$/kg | 9.91 | 6.60 | 5.51 | 5.00 | 5.00 | 5.00 |

[a] based on [28] and considering 5 % discount for quantity buyers; [b] CNG: Compressed Natural Gas, prices based on [28]; [c] LNG: Liquefied Natural Gas, prices based on [29]; [d] based on [30]; [e] based on [31]

The $CO_2$ regulation is set to current legislation. For vehicles of the 3.5 ton GVW segment the initial TTW $CO_2$ target value is 175 g $CO_2$/km applied in 2017. In 2020 147 g $CO_2$/km becomes obligatory. For the remaining vehicle segments no $CO_2$ legislation is in place.

The number of new registrations is held constant at the average level of the years from 2005 to 2014 with in total 271,447 new registrations in Germany. The same applies for the vehicle segment share. The transport task shares are determined based on the special analysis of statistical road freight transport data of the year 2014 performed by the German Federal Office for Motor Vehicles and also held constant over time. Table 2 contains the German road haulage market key parameters considered.

Table 2: German road haulage market key parameters considered

| | Vehicle segment | | | | | |
|---|---|---|---|---|---|---|
| | 3.5 ton GWV | 7.5 ton GVW | 12 ton GVW | 18 ton GVW | 26 ton GVW | 40 ton GVW |
| Vehicle segment share | 75 % | 7 % | 3 % | 2 % | 4 % | 9 % |
| Urban freight distribution share | 60 % | 99 % | 42 % | 70 % | 70 % | 32 % |
| Regional freight distribution share | 26 % | 1 % | 40 % | 24 % | 25 % | 35 % |
| Long distance freight transport share | 14 % | - | 18 % | 6 % | 5 % | 33 % |

Table 3 comprises the basic parameters of the customer types considered. The basic parameters relevant for the calculation of the specific costs per unit regarding the different components are given in Table 4.

Table 3: Basic parameter of the customer types considered

| | Customer type | | | |
|---|---|---|---|---|
| | Innovator | Early adopter | Conservative laggards | Doubters |
| Customer type share | 3.2 % | 8.6 % | 44.1 % | 44.1 % |
| Max. payback period | Vehicles service life | 4 years | 2 years | 1 year |
| Interest rate | 4.2 % | 4.2 % | 4.2 % | 4.2 % |
| Corporate tax rate | 30 % | 30 % | 30 % | 30 % |

Table 4: Parameters for the calculation of the specific component costs

| Component | Production volume apiece | Specific cost | Learning rate |
|---|---|---|---|
| Electric machine [a] | 500,000 | 20 $EUR_{2010}$/kW | 84 % |
| Power electronics [a] | 500,000 | 16 $EUR_{2010}$/kW | 81 % |
| Battery system (high energy) [a] | 100,000 | 266 $EUR_{2010}$/kWh | 86 % |
| Battery system (high power) [a] | 100,000 | 470 $EUR_{2010}$/kWh | 94 % |
| Fuel cell system (LTPEM) [a] | 100,000 | 51 $EUR_{2010}$/kW | 78 % |
| Hydrogen storage system (70 MPa) [b] | 80,000 | 558 $EUR_{2010}$/kg $H_2$ | 87 % |
| Hydrogen storage system (35 MPa) [b] | 80,000 | 457 $EUR_{2010}$/kg $H_2$ | 85 % |
| LNG storage system [c] | 100,000 | 34 $EUR_{2010}$/kg LNG | 93 % |

[a] based on DLR bottom-up cost models; [b] based on [32]; [c] based on [33]

As described within [21], the vehicle concepts are configured considering the current state of the art. For parallel hybrids, MHEV, FHEV, and PHEV, it is assumed that the conventional ICE-D powertrain is supplemented by the components of electrification with different functionalities and battery sizes. Relating to BEV two different configurations in terms of the battery size and thus range are considered. One version allows for 150 km range and the other allows for 300 km range. The REEV is a serial hybrid, based on the BEV with 150 km range and a downsized internal combustion engine or a fuel cell system as range extender module operating in its best efficiency point. The fuel cell system power of the FCEV corresponds to 50 % of the reference vehicles traction power. No different vehicle configurations regarding the transport tasks are considered. The energy consumption and thus the TtW $CO_2$ emissions for the different vehicles are determined based on reverse longitudinal dynamic calculations using the World-Harmonized Light-duty vehicles Test Procedure (WLTP) for the 3.5 ton GVW segment. For the remaining vehicle segments the World Harmonized Vehicle Cycle (WHVC) is used.

# 4 Results

## 4.1 New vehicle fleet

Figure 2 shows the results of the reference scenario for the German road haulage market of new light (LCV) and heavy commercial vehicle (HCV) registrations regarding the years 2015, 2020, 2025, 2030, 2035 and 2040. The results of the six modelled vehicle segments and the three different transport tasks are aggregated according to their sales share. Hybrid electric vehicles and vehicles with natural gas as energy carrier gain significant market shares. Driven by the tightening of the $CO_2$ regulation for light commercial vehicles hybridized powertrains, especially MHEV-D vehicle concepts play an important role in reaching the targets set. In 2020, the MHEV-D market share reached is 48 % and gaining up to 52 % in 2040. Due to overall less expenditure for Maintenance & Repair for vehicles using compressed natural gas, compared to the ICE-D reference vehicle, the disadvantages in fuel consumption are overcompensated resulting in a continuous growth in marked shares for ICE-NG vehicle concepts. ICE-NG market share increases from 3 % in 2020 up to 7 % in 2040. MHEV-NG vehicles contribute with 7 % market share to the observance of the $CO_2$ target value in 2020 with a reduction of the market share to 2.5 % in 2040 due to an increasing energy efficiency of the ICE-NG vehicle. FHEV-D, FHEV-NG and PHEV-NG vehicle concepts remain in niche markets. However, the market shares in the niche markets vary across the different powertrain types between 0.7 % and 3.0 %. BEV and FCEV vehicle concepts are not competitive under the given framework.

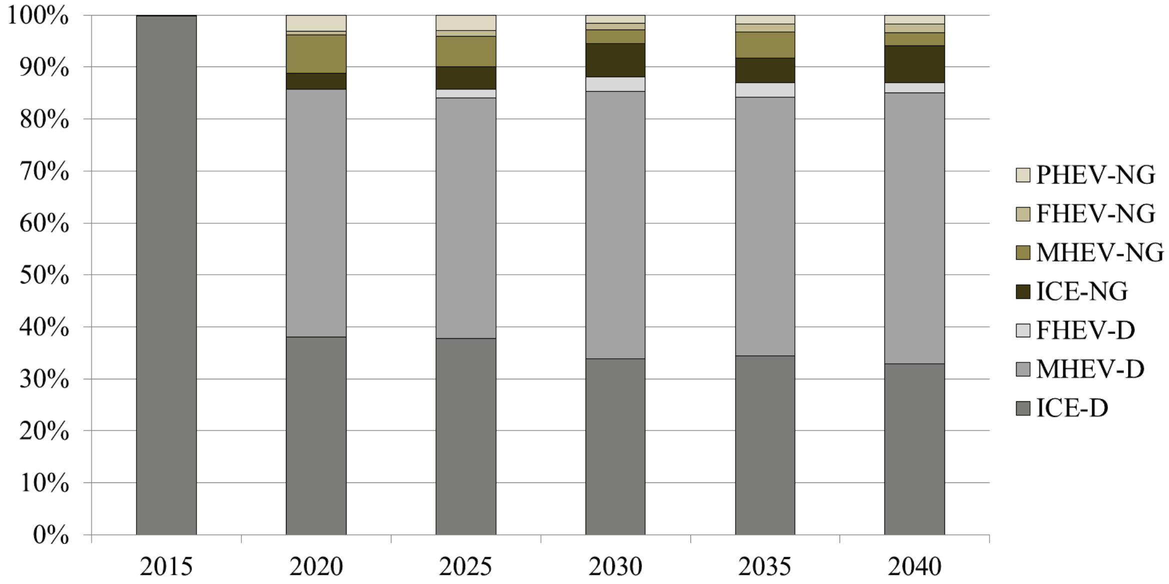


Figure 2: Results of the reference scenario for the German road haulage market of new light and heavy commercial vehicle registrations for the years 2015, 2020, 2025, 2030, 2035 and 2040

When looking separately at the market for light (3.5t GVW segment) and heavy commercial vehicles (remaining segments) it becomes apparent that under the given framework particularly MHEV-D vehicle concepts are required in order to observe the existing $CO_2$ regulation for light commercial vehicles. From 2020, the MHEV-D vehicle concepts totally replace the ICE-D vehicle concepts in the urban freight distribution market. In the regional freight distribution market MHEV-D and FHEV-D gaining significant market shares, whereas in the long distance freight transport market a mix of the vehicle concepts using natural gas as energy carrier dominate the new registrations over time. Regarding the heavy commercial vehicle market, the market share of ICE-D vehicle concepts remain at a dominant level. ICE-CNG vehicle concepts gaining market shares throughout the HCV segments and transport tasks, mainly in regional distribution and long distance freight transport applications. ICE-LNG vehicle concepts do not gain relevant market shares. The market share of MHEV-D, FHEV-D, MHEV-CNG and FHEV-CNG are growing over time but remain in niche markets (see Figure 3).

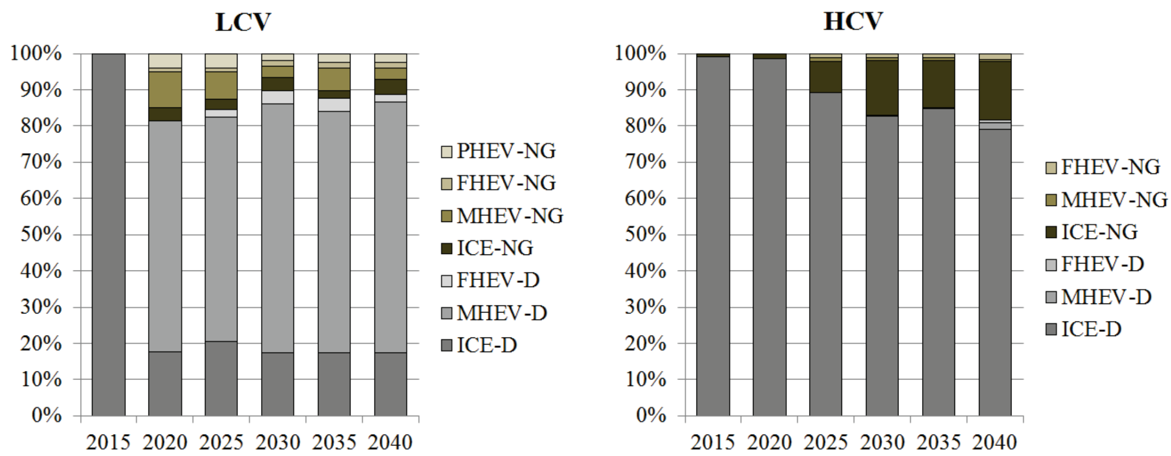


Figure 3: Results of the reference scenario for the German road haulage market separated into new light commercial vehicle registrations (on the left) and heavy commercial vehicle registrations (on the right) for the years 2015, 2020, 2025, 2030, 2035 and 2040

Altogether and under the given scenario parameters, only vehicle concepts using an internal combustion engine are relevant. A market potential for hybrid electric vehicles in the LCV market and for vehicles using compressed natural gas as energy carrier in the HCV market was identified. Battery electric vehicles and fuel cell electric vehicles are not cost competitive and thus do not enter the market.

### 4.2 Sensitivity analysis

A sensitivity analysis was applied to identify critical factors and to increase the understanding of the relationship between model input and output variables. For this purpose, numerous parameters are varied. The results of the sensitivity analysis are shown exemplary for the ICE-D and ICE-CNG vehicle concepts (see Figure 4).

One of the most critical parameter is the resale value. Furthermore, increasing the payback period for all customer types to the maximum (vehicles service life) impact the new registrations of the ICE-D vehicle concept. In addition, differences in urban, regional and highway driving shares and not considering the tax advantage show significant influence. Beside the resale value, the diesel and CNG price variation show the most significant influence on the new registrations of the ICE-CNG vehicle concept.

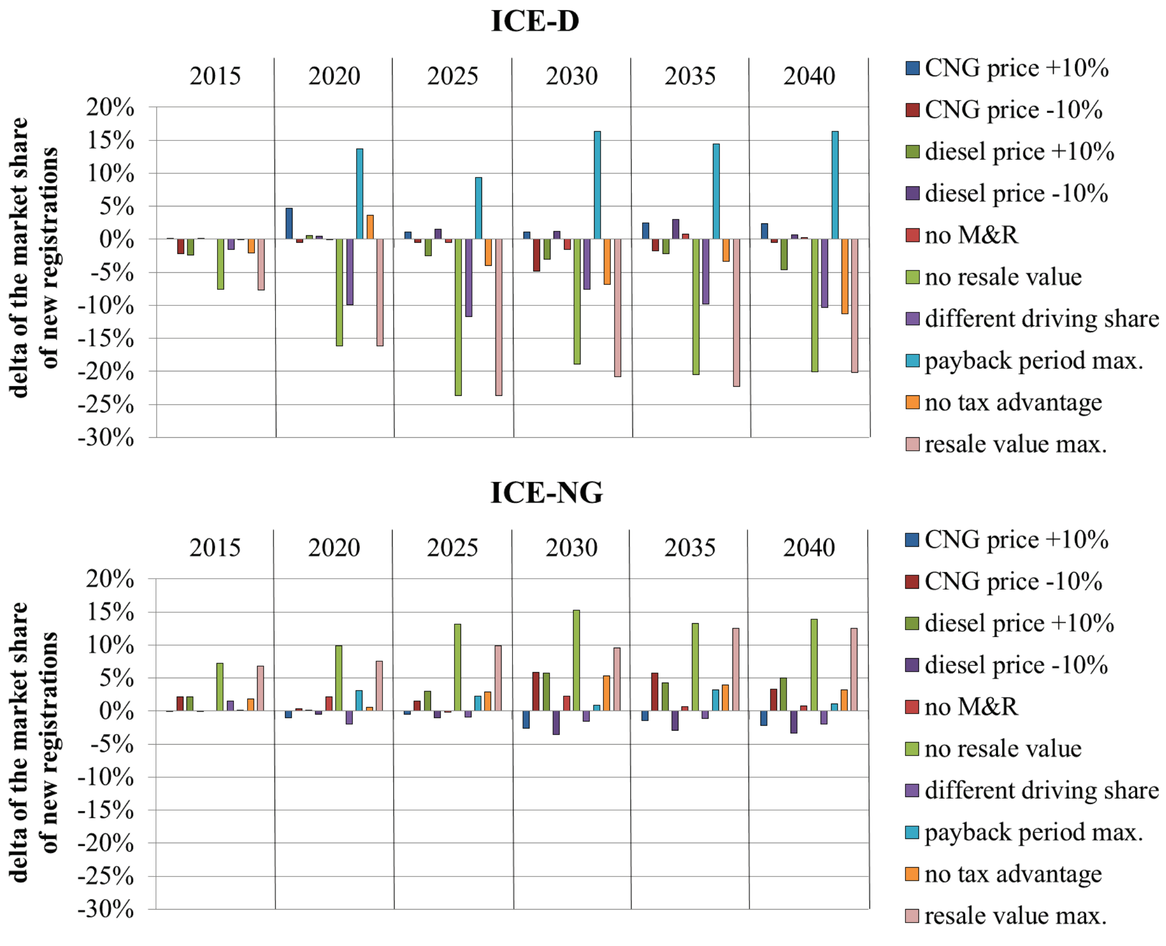


Figure 4: Results of the sensitivity analysis regarding the ICE-D and ICE-NG vehicle concepts

## 5 Conclusion

A modelling approach for the German road haulage market of new light and heavy commercial vehicle registrations with different gross vehicle weights and competing powertrain technologies considering different transport tasks was introduced. Via a reference scenario the new registrations of alternative powertrain technologies for the years 2015, 2020, 2025, 2030, 2035 and 2040 was shown for the German road haulage market in total and separately for the light and heavy commercial vehicle market. Due to the implementation and tightening of $CO_2$ regulations advanced powertrain technologies are required in order to meet the targets set and thus faster entering the market. In case no $CO_2$ regulation is in place, the development of electrified powertrains is modest. Vehicles using an internal combustion engine dominate the market. A market potential for hybrid electric vehicles in the LCV market and for vehicles using compressed natural gas as energy carrier in the HCV market was identified. Battery electric vehicles and fuel cell electric vehicles are not cost competitive and thus do not enter the market in the reference scenario. Most critical parameters identified are the resale value, the required payback period and the underlying driving share.

Basically, the development of alternative powertrain technologies in the light and heavy commercial vehicle market is highly uncertain. Therefore, the presented model approach allows for the analysis under which market conditions alternative powertrain technologies can enter the market and gain market shares in order to face the challenge to reduce the emissions caused by road freight vehicles. Therefore and on the one hand, it was developed to support strategic decisions of policy makers, e.g. regarding the implementation of a $CO_2$ regulation framework for heavy commercial vehicles. On the other hand the model outputs support strategic decisions of manufacturers, e.g. regarding the identification of future market potentials for alternative vehicle concepts.

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## Authors

**Florian Kleiner** is a researcher at the German Aerospace Center (DLR). He studied Business Administration and Engineering at the Pforzheim University and the University of Technology Sydney (UTS). After graduating his Master degree in energy management with specialization in renewable energies 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 since 2012.

**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.