# Well-to-wheel emission factors for future cars in Germany with a focus on fleet composition, new technologies and emissions from energy supplies

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**Abstract:**

Until today, road transport is largely fossil fuel driven and contributes significantly to greenhouse gas emissions and air pollutants. In order to assess the impact of development pathways of future transport, new emission factors for emerging technologies and a shift in the assessment framework that includes well-to-tank emissions is needed. The focus of this study is to provide emission factors for future passenger cars and fleets and offer an approach to comprehensively assess emission effects in future studies. Our scenario storyline approach imbeds different levels of changes in consideration of plausibility and consistency. We developed three pathways for Germany up to 2040 in order to capture the interdependencies of measures and developments. We hereby consistently modified the progress in transport technologies and in power generation together with changes in fleet compositions. Furthermore, we developed emission factors and energy consumption factors for plug-in hybrid and electric vehicles and expanded the conventional tank-to-wheel emission factors by including well-to-tank emissions derived from consistent energy scenarios. The development of emission factors depends on multiple factors, including vehicle and engine size. Furthermore, electrification shifts the emissions from tailpipe to power generation. Particularly for nitrogen oxides and particulate matter emissions, electric power generation for transport purposes could contribute significantly to ambient air emissions in the future, while tailpipe emissions can be expected to decline substantially.

Keywords: car emission, fleet-wide emission factor, German transport scenario, well-to-wheel, energy scenario

**Highlights:**

- Emission factors for future road traffic need to take energy supply into account
- Technological changes in energy and transport needs to be analysed integratively
- Three scenario storylines for Germany 2040 are taken into consideration
- New emission and consumption data are provided for plug-in hybrid and electric cars
- Scenarios analysed for Germany in 2040 show significant quantitative differences
- While tailpipe emissions decline power generation could remain significant

## 1. Introduction

Road transport today is a major contributor to greenhouse gas emissions and local air pollution, particularly nitrogen oxides and particulate matter (EEA 2015). Furthermore, projections of future road transport indicate strong increase in global demand (ITF 2017) and fuel consumed (IEA 2009). The ability to mitigate negative environmental impacts from road transport in the future depends on the successful introduction of new technologies in the market and the achievements in improving efficiencies. An appropriate way to evaluate potential future development pathways of road transport is the application of scenario techniques.

Plausibility and consistency are two important aspects to be considered in scenario analysis. Technological developments and behavioural changes have interactions and always take place in a societal context. Designing plausible and consistent context scenarios is one strength of storyline and simulation approaches. With regard to road transport, the combination of qualitative and quantitative aspects entails the consistent inclusion of developments in the energy sector, since future mobility will be increasingly propelled with electricity.

Within the project Transport and the Environment (Henning et al., 2015), twelve institutes of the German Aerospace Center (DLR) developed three explorative scenarios of the German transport system up to 2040. The scenarios were labelled *Reference*, *Free Play* and *Regulated Shift* (Table 1). The scenario development applied a storyline and simulation approach to create consistent context settings, and identify societal levers affecting both, the transport and the energy system (Seum et al. forthcoming).

This paper focusses on the translation of these scenario storylines into emission factors for future cars and fleets. We include changes in the vehicle stock as well as the size of engines and vehicles, consistent with the scenario storylines. We developed emission factors for hybrid, plug-in-hybrid, battery-electric, and fuel cell technologies based on own measurements and with an advanced model-based approach. Additionally, we considered the energy system and the emissions from electricity generation based on consistent long-term energy scenarios.

In the following paper, we discuss the approach to expand existing emission factors provided by the Handbook Emission Factors for Road Transport (HBEFA 2017) in scenario consistent ways. We present our approach for passenger cars as an example. We will focus hereby on four main pollutants of road transportation, namely carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), and fine particulate matter ($PM_{10}$). Our system boundary includes refinery processes and electricity generation, but excludes the extraction and transport of raw materials to those plants. Resulting are well-to-wheel factors for German road transport up to 2040.

*Table 1: Snapshot of the three VEU scenarios.*

| Reference scenario | Free Play scenario | Regulated Shift scenario |
|---|---|---|
| Represents a continuation of currently existing trends, but also moderate improvements regarding the implementation of new technologies and the use of renewable energies (RE) in the transport sector. | Society follows a liberal market-economic logic. The state in this scenario takes a step back, trying to avoid hampering developments through an overburden of regulations. | Society implements more stringent regulations, combined with investments in infrastructure for public transport and financial instruments to foster the development of certain clean technologies. |

## 2. Problem statement and approach

Together with the European legislation for limiting emissions of on-road vehicles, a set of emission modelling tools have been developed (e.g. Ntziachristos et al., 2009; Keller et al., 2017). In combination with transport demand models, such as TREMOD or TREMOVE, emission models are primarily established to monitor emissions and to create national inventories. Those models allow, to a limited extent, the outlook into the future, but neglect new vehicle technologies and interdependencies with regard to technology developments. In addition, many scientific studies have been published addressing the improvement of emission factors and models for road transportation and providing data sets as basis for emission calculations (e.g., Voutsis et al., 2017; Franco et al., 2013). However, emission factors for new technologies that would allow comparative assessments are missing.

More recently, the discussion shifted to the representativeness of emission factors and model results, as evidence of increasing gaps between real-world driving emissions and emission factors emerged. Here two phenomena are observed. First, the increasing gap between real-world fuel consumption and dynamometer testbed derived values. Second, the exceedance of legal emissions limits, in particular of $NO_x$ emissions from diesel fuelled cars. The first is due to a large leeway in the standard test procedure and particular a limited operational coverage of the old test driving cycle (NEDC – New European Driving Cycle). Fontaras et al. (2017) discusses the influencing factors for fuel consumed and evaluates the introduction of the new test driving cycle (WLTP – Worldwide harmonized Light-duty Test Procedure). The second phenomena stems from technical limits of emission control devices and manipulations that led to optimized emission figures under test conditions and often higher emissions under real driving conditions. The focus here was on $NO_x$ emissions (e.g. Kousoulidou et al., 2013; O'Driscoll et al., 2016), which are particularly elevated with diesel cars.

The introduction of new technologies appears in a societal context and interdependencies need to be considered. The effect of societal levers (e.g. financial measures, regulation, investments) on a system level is hereby in the centre of our explorative scenario analysis. For this reason, scenario-based factor developments are an advancement to existing approaches. On the one hand, possible development pathways of vehicle concepts, their sizes and drivetrains and technology implementation need to be addressed. On the other hand, the increasing electrification of mobility in the form of battery-powered vehicles and hybrids results in well-to-tank emissions from power generation that must be taken into account in a consistent and plausible manner. Therefore, our basic approach is a coupling of scenario-based simulations of future vehicle fleets, an update and extension of emission factors for different vehicle categories, and an integration of scenario-based estimations of the future emissions from the energy supply. The following sections provide a detailed description of the approach.

The Handbook of Emission Factors (HBEFA 2017, Keller et al., 2017) provides a good starting point for developing fleet-wide emission factors for Europe. HBEFA provides emission factors for passenger cars, light and heavy duty vehicles and buses with conventional engines. The factors are split according to the propulsion systems "diesel", "gasoline" and "gas" (CNG) and the corresponding EURO emission classes. Emission factors for passenger cars are split in engine size categories (smaller than 1.4 litre, 1.4 up to 2.0 litre and larger than 2.0 litre). Another feature of HBEFA is the distribution of vehicle-kilometre travelled on three road categories – urban, extra-urban and highway. The HBEFA Handbook offers emission factors for the years 1995 to 2030 in five year steps. The Handbook was originally developed based on emission measurements of existing vehicles and on vehicle simulations with the model PHEM. The emission factors in HBEFA are approximations of real driving emissions and fuel consumption. HBEFA was developed on behalf of the Environmental Protection Agencies of Germany, Switzerland and Austria (TU Graz, 2009). In the meantime, further countries (Sweden, Norway, and France) as well as the JRC (European Research Centre of the European Commission) are supporting HBEFA.

In the project Transport and the Environment, we have developed three possible future explorative scenarios for Germany up to 2040 (Seum et al., 2017). In a structured approach, combining qualitative and quantitative methods, the plausible and consistent storylines of the *Reference*, the *Free Play* and the *Regulated Shift* Scenario were created (Seum et al. forthcoming). In each scenario, societal levers were identified and effects for the transport and energy system were modelled. The three scenarios affect future emissions of passenger vehicles through different evolutions of the transport system with an effect on vehicle fleets. For example, the *Reference* scenario plots a continuation of current trends with the *Free Play* and *Regulated Shift* scenarios developing in opposite directions. In the *Free Play* scenario the propulsion systems are in a coequal competition and public transit deteriorates, except for central and dense urban areas. Vice versa, the *Regulated Shift* scenario assumes policies that promote walking, biking, public transit and advanced vehicle technologies, by at the same time making private car ownership more expensive and parking less available. One consequence of those diverging stories is different total numbers of passenger cars. In the *Reference* case, 43 million passenger cars will be on the road in Germany in 2040, whereas in the *Free Play* scenario it will be 45 million and in the *Regulated Shift* scenario the stock of passenger cars will sum to only 35 million. Thus, the vehicle fleet provided by HBEFA for the year 2030 needed to be modified according to those scenario developments and emission factors needed to be extended to the year 2040.

## 3. Methodology for deriving scenario-based emission factors

### 3.1. Passenger car size development and composition

The scenario dependent passenger car fleets were modified in two fields. First, the development of vehicle and engine size was projected. Second, the market penetration of propulsion technologies was modelled. The approach with regard to the non-technical fleet composition is presented in this section. The technical aspects are discussed in the following section.

To date there is no standard classification system for the passenger car market with regard to size and segments. Segments, however, are often used to analyse vehicle market trends. The German market for passenger cars differentiates between thirteen segments (KBA, 2016), which correspond to largely the European passenger car classes (EEC 1999) (Table 2). For the recent development, we analysed the car stock for the years 2008-2015. The largest segment is that of compact cars, which represent 26% of the vehicle in stock in 2015 (KBA, 2016). However, the fastest growing market segments are those of SUV and off-road vehicles, which nearly tripled in stock between 2008 and 2015. For our purpose to project vehicle developments according to certain scenario assumptions, we aimed to simplify the vehicle segments into three vehicle size classes: small (S), medium (M) and large (L) (see Table 2). The past decade of passenger car development is characterized by a strong growth of the segments S (+14%, 2008–2015) and L (+15%), whereas the medium size cars M only grew by 7%. Simultaneously a trend in engine downsizing by at the same time an increase in average engine power can be observed (Fontaras et al., 2017; ICCT, 2018).

Within our scenario analysis, we implemented measures that affect both, trends in vehicle size and trends in engine sizes. Since HBEFA plots the fleet performance based on the distribution of engine size in terms of cubic capacity, the allocation of engine sizes to vehicle sizes is necessary.

The data available to allocate engine sizes to passenger car segments are average displacement per KBA segment and motorization information from the ADAC database on cars (ADAC, 2016). For each segment three to four most selling cars were selected (e.g. VW Polo, Toyota Yaris, Peugeot 207 and Citroen C3 for the Supermini segment). Largest and smallest engines available for those cars were taken from the ADAC database on cars. Together with the average engine size, we applied a standard distribution of engine sizes per vehicle segment. Finally we adjusted the selection, (i.e. excluded some extreme motorization cases), in order to calibrate the engine distribution to data provided by HBEFA for 2015. The matched distribution of engines to passenger car segments is presented in Table 3.

*Table 2: Classification of German passenger car stock, 2015 shares and growth 2008 – 2015 (KBA 2016)*

| German car segments | EU classes | S, M, L allocation | Share in stock 2015 | Growth 2008 - 2015 |
|---|---|---|---|---|
| City car | A | S | 7.0% | 36% |
| Supermini | B | S | 20.5% | 8% |
| Small family car | C | M | 27.3% | 3% |
| Large familiy car | D | M | 16.3% | - 15% |
| Executive | E | L | 4.8% | - 15% |
| Luxury car | F | L | 0.6% | 20% |
| Compact SUV | J | M | 4.2% | 180% |
| Large 4x4 | J | L | 4.3% | NA |
| Sports car | S | L | 1.9% | 35% |
| Vans | M | M | 4.6% | 34% |
| Minibus | M | L | 4.8% | 16% |
| Utilities | M | L | 3.8% | 32% |

*Note: the category “caravans” was excluded from the analysis.*

*Table 3: Allocation of engine sizes to passenger car segments and S, M, L classification in 2015.*

| German car segments | S, M, L allocation | Engines < 1.4 l | Engines 1.4 < 2.0 l | Engines >= 2.0 l |
|---|---|---|---|---|
| City car | S | 100% | 0% | 0% |
| Supermini | S | 90% | 10% | 0% |
| Small family car | M | 23% | 77% | 0% |
| Large familiy car | M | 5% | 58% | 37% |
| Executive | L | 0% | 20% | 80% |
| Luxury car | L | 0% | 5% | 95% |
| Compact SUV | M | 7% | 88% | 5% |
| Large 4x4 | L | 5% | 44% | 51% |
| Sports car | L | 1% | 14% | 85% |
| Vans | M | 1% | 99% | 0% |
| Minibus | L | 5% | 90% | 5% |
| Utilities | L | 2% | 82% | 16% |

The setting of several assumptions provided below then led to the development of the vehicle size distribution in the three scenarios. The assumptions were calibrated by matching the *Reference* scenario engine size distribution 2030 with those of the HBEFA data for 2030. For the other two scenarios we adjusted the segment and engine distribution based on demographic and behaviour assumptions that were qualitatively set and that are consistent to the scenario storylines. The resulting trends are:

- *Reference* scenario: Trend towards small vehicles and SUV continues. S segment increases by 2%, L increases by 3%. M declines by 2%. For the engine development we assume a general downsizing trend, but with a high power trend in upscale segments. This results in 14% more engines with <1.4 l and 4% less engines with >=2.0 l cubic capacity.

- *Free Play* scenario: The comparatively low cost for private cars lead to an increased trend towards larger vehicles and SUV. S segment decreases by 40%, M increases by 10% and L increases by 30%. For the engine development we assumed a trend to higher powered vehicles that offset downsizing trends. This results in 5% less engines <1.4 l and 10% more engines with >=2.0 l cubic capacity.

- *Regulated Shift* scenario: Higher costs for private car use and an increased awareness for environmental issues lead to strong shift towards smaller cars. S segment increases by 20%, M increases by 5% and L decreases by 40%. For the engine development we assume a stronger trend towards downsizing compared to the *Reference*. This results in 50% more engines with <1.4 l and 50% less engines >=2.0 l cubic capacity.

### 3.2. New emission factors for passenger cars

Additionally to conventional gasoline (G) and diesel (D) vehicles found in HBEFA, we consider diesel and gasoline full hybrid electric vehicle (D-HEV and G-HEV), gasoline plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEV). The emission factors for hybrid vehicles were developed using our own measurements on the DLR test-bed as well as literature reviews (EPA, 2016; Kugler et al., 2016; Suarez-Bertoa and Astorga, 2016). Furthermore, we modelled the energy demand from electric vehicles and the electrically driven proportion of plug-in hybrid vehicles. Emissions factors, which describe the mass of different emitted gases per kilometre, were developed for each type of drive-train and vehicle size within the three scenarios. As the scenarios described above illustrate the development of transport into the future, we needed to develop these emission factors for the reference years 2030 and 2040. Emission factors for 2010 were provided by HBEFA.

Energy consumption and carbon dioxide emissions were simulated with the VECTOR21 tool, (Mock, 2010) including a dedicated module for PHEV, using the world harmonized light-duty vehicle test cycle (WLTC) (Kugler et al., 2017; Schimeczek, 2015). Within this model, the energy consumption of different vehicle concepts is calculated based on the efficiency of the driving machines and gear transmission. The efficiencies are determined on the basis of simplified efficiency maps. The scenario settings as described in Table 1 and further outlined in Seum et al. (forthcoming) determine the extent of user demand on increased energy efficiency of each drive train. Based on this demand, costs for certain efficiency technologies and drive-trains evolve differently and lead to a variance in the future vehicle market. Therefore, fuel efficiency and electric energy consumption of future drive-trains diverge in the three scenarios. In case of electrified vehicles (HEV, PHEV and BEV), the efficiency technologies additionally affect the electric range and thus the absolute direct emissions and energy consumption of the vehicle in operation. For hybrid vehicles, the main influencing aspect for the energy efficiency and the share of fossil driving is the electric range. We applied this range to determine the utility factors for each vehicle. Compared to conventional vehicles, hybrid vehicles achieve a better fuel efficiency on all roads due to the permanent electric assistance of the hybrid system in addition to portions of pure electric driving in particular on urban roads (Table *4*). The tank-to-wheel $CO_2$ emissions of the vehicles in 2030 and 2040 are directly calculated based on the resulting fuel consumption with a ratio of 2.3 kg $CO_2$ per litre of gasoline and 2.4 kg $CO_2$ per litre of diesel.

In the case of conventional gasoline and diesel vehicles, we used emission factors for air pollutants from HBEFA (v3.3) up to the reference year 2030. Emission factors for cars that use compressed natural gas (CNG) were derived from BMU (2009) and the corresponding data sets in the GEMIS database (IINAS 2017). It should be noted that data on emissions from CNG vehicles is sparse and particularly the future prospects are largely unknown. As for air pollutant emissions, in particular CO, $NO_x$ and PM, we expect the emission factors for conventional technologies to decline in the future, i.e. beyond 2030, due to stricter regulations and controls in the upcoming years. For 2040, we assumed all vehicles would be EURO 6 compliant.

*Table 4: Tank-to wheel energy consumption per drive train in MJ/km in 2040 (G = gasoline, D = diesel, G-HEV = gasoline-hybrid-vehicles, D-HEV = diesel-hybrid-vehicles, PHEV (fuel) = fossil fuel portion of plug-in-hybrid-vehicles (gasoline), PHEV (electricity) = electricity from grid portion of plug-in-hybrid-vehicles (gasoline), BEV = battery-electric-vehicles, FCEV = fuel-cell-electric-vehicles)*

| **Drive-train** | **Reference** | | | **Free Play** | | | **Regulated Shift** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **S** | **M** | **L** | **S** | **M** | **L** | **S** | **M** | **L** |
| G | 1.46 | 1.59 | 3.25 | 1.47 | 1.74 | 2.85 | 1.46 | 1.66 | 3.24 |
| D | 1.30 | 1.51 | 1.61 | 1.30 | 1.62 | 1.75 | 1.28 | 1.42 | 1.76 |
| G-HEV | 1.01 | 1.07 | 1.42 | 1.39 | 1.52 | 1.82 | 1.05 | 1.10 | 1.56 |
| D-HEV | 0.80 | 1.00 | 1.49 | 0.96 | 1.22 | 1.79 | 0.94 | 1.07 | 2.13 |
| PHEV (fuel) | - | 1.51 | 2.09 | - | 1.56 | 2.23 | 1.49 | 1.5 | 2.11 |
| PHEV (electricity) | - | 0.53 | 0.55 | - | 0.54 | 0.58 | 0.52 | 0.52 | 0.56 |
| BEV (electricity) | 0.45 | 0.50 | 0.52 | 0.45 | 0.56 | 0.65 | 0.44 | 0.55 | 0.60 |
| FCEV (hydrogen) | - | - | - | - | - | - | - | 1.23 | 1.7 |

With regard to hybrid technologies, studies on HEV emissions report possible emission savings of up to 60% for particular pollutants (Fontaras et al., 2008; Alvarez and Weilenmann, 2012; Suarez-Bertoa and Astorga, 2016). As there are large uncertainties concerning the real reduction potential on the road, a conservative reduction of 10% in addition to the reduction of conventional EURO 6 vehicle was assumed. Furthermore, a 10% share of electric driving in cities was assumed for HEV as default. We recognize the large uncertainty in this assumption, but due to a lack of data on the share of electric driving of HEVs and based on estimations on energy recuperation and battery capacity, the 10% share is seen as a conservative estimation on possible electric ranges in urban driving.

The emission factors of PHEV are based on own measurements of emissions of a mid-size PHEV on the DLR vehicle dynamometer (exemplarily described in Kugler et al., 2016). These measurements delivered the emissions for the different road categories and temperatures as well as a utility factor to take into account the different electric driving shares in urban, extra-urban and highway driving situations. The utility factor implies the share of driving in the charge depletion (CD) mode and charge sustaining (CS) mode of a PHEV. In the CD mode, the battery provides sufficient energy for mainly electric driving, while in the CS mode the battery's state-of-charge (SOC) is at a low level and the vehicle is operated mainly with the internal combustion engine. For our calculation, the utility factors were taken from the WLTP standard and vary between 0.65 and 0.77, depending on vehicle size, reference year and scenario. The basic pollutant emissions are assumed to be equal for all vehicle sizes. Due to the utility factor approach, absolute $CO_2$ and pollutant emissions differ between the sizes.

In order to address the spatial distribution of emissions and the differences of energy consumption and emissions in different traffic situations, factors for three road categories – urban, extra-urban and highway – were applied. In case of conventional vehicles, the pollutant emission factors were taken from the HBEFA database accordingly. For energy consumption and $CO_2$ emissions of conventional vehicles as well as for the alternative vehicles in general, WLTC simulation and measurement data are allocated to the segments of the cycle. In a final calculation step, emissions and energy consumptions are weighted according to the shares of average driving situation in Germany, which is for the *Reference* scenario 32% urban driving, 39% of rural driving, 29% of highway driving in 2010 and 34% urban, 36% rural and 30% highway driving in 2040 (Winkler et al. 2017). Additionally, car-km travelled for the vehicle size categories per road type differs in each scenario slightly. For the electrified transport modes and vehicles we applied average emission factors from the German power generation system based on scenarios (see next section).

### 3.3. Emissions from electricity and fuel supply

The shift from fossil fuels to electric energy can significantly reduce transport emissions of greenhouse gases and air pollutants. Several studies have already shown that this requires a substantial shift towards renewable energy (RE) sources and flexible infrastructures in the power system, while at the same time reducing thermal power generators based on fossil fuels (e.g., McLaren et al., 2016; Ökoinstitut, 2016; Luca de Tena and Pregger, 2018). Consistent with the socio-economic assumptions and normative political targets, we therefore assumed different developments of the power system for the three scenarios. A successful continuation of the German 'Energiewende', i.e. target-oriented RE expansion in power generation results in around 78% renewable electricity in 2040 in the *Regulated Shift* scenario. In contrast, this share is around 50% in the *Reference* case without additional politically set incentives and assumed to be only 40% in the *Free Play* scenario, equivalent to a stop of further RE expansion around the year 2020.

Consistent with the assumed political boundary conditions and the targets in transport, the scenarios differ primarily with regard to the development of renewable electricity generation, but also with regard to the demand for electricity in individual sectors due to different efficiency assumptions. Table 5 summarizes the assumptions for the German energy system. The highest renewable share of gross power generation is reached in the *Regulated Shift* scenario. Electricity demand for the sectors industry, residential, and services and commerce is derived from Schlesinger et al. (2014) for the *Reference* and the *Free Play* scenarios assuming in both cases the same efficiency path. Assumed electricity demand in the *Regulated Shift* scenario is based on normative scenarios achieving the political $CO_2$ emission and efficiency targets, namely the 'Target scenario' from Schlesinger et al. (2014) and the 'Long-term scenarios' from Pregger et al. (2013). All scenarios take into account decreasing intensities of the 'classical' consumers but increasing demand from implementing new technologies. These are above all heat pumps and electric boilers in the heating sector and electric vehicles in transportation, serving also as flexibility options (power-to-x) in future energy systems with high shares of variable renewable power.

The scenarios were calculated with a scenario model developed by DLR for Germany using the commercial software Mesap/PlaNet (Modular Energy System Analysis and Planning Environment, seven2one, Karlsruhe). The philosophy and basic structure of the so-called "accounting framework" were presented in Schlenzig (1999). The Mesap-based energy models were used by DLR in numerous projects for the development of normative scenarios (e.g. (Krewitt et al., 2009; Teske et al., 2018; Pregger et al., 2019).

*Table 5: Main energy scenario parameters for 2040: electricity consumption and generation structure*

| Parameter | Base year 2010 | Reference 2040 | Free Play 2040 | Regulated Shift 2040 |
|---|---|---|---|---|
| Gross electricity consumption [TWh/yr] | 612 | 574 | 560 | 560 |
| thereof transport (incl. for hydrogen) | 20 | 35 | 17 | 126 |
| Share of power generation: | | | | |
| Renewables without biomass | 11% | 41% | 31% | 65% |
| Biomass | 5.4% | 10% | 9% | 13% |
| Hard coal | 18% | 14% | 21% | 3% |
| Lignite | 23% | 18% | 22% | 0% |
| Non-biogenic waste | 4% | 1% | 1% | 1% |
| Oil | 1% | 0% | 0% | 0% |
| Natural gas | 14% | 16% | 15% | 18% |

Emission factors for thermal power generators were derived from emission estimates and factors provided by the German Environment Agency (UBA, 2015), used for emission reporting. While energy models distinguish sectors and fuels, possibly with subcategories such as cogeneration, emission factors usually refer to specific plant sizes and permit requirements. Since an assignment of the emission factors could only be made on an aggregated level, we applied a top-down calibration of our emission estimation based on bottom-up calculations from official emission reporting for the energy sector (UBA, 2016a). The calibration was done for the years 2009, 2011, 2012 and 2014. Emission factors were then assumed to stay constant in the future as the further development of air pollution regulation in the future is unknown. Therefore changes in our average specific emissions from electricity supply are only due to the changing generation mix. Emission factors for the supply of fossil fuels are own estimations representing emissions from industrial process heating, modified by the calibration. The resulting specific direct emissions for the supply of electricity and fuels referring to MJ consumed were derived from the scenario results for the refinery production, the fuel consumption in transportation and estimated emissions in the conversion sector derived from the official emission reporting (UBA, 2016b).

## 4. Results and discussion

In this section we compile the results of our analysis above. First, the final segment and engine size shares are presented. Second, tank-to-wheel (tailpipe) emissions and well-to-tank emissions for electricity and fuels are presented separately. Finally, we provide an overview of total emissions (well-to-wheel) by scenario and drivetrain.

*Table 6: Scenario development for 2040 of passenger car segment distributions and engine sizes distribution for gasoline and diesel cars. (S = small, M = medium, L = large)*

| | | **% share of segments** | **Distribution of engine size for gasoline and diesel cars** | | |
|---|---|---|---|---|---|
| **Scenario 2040** | **Segment** | **for all technologies** | **Engines < 1.4 l** | **Engines 1.4 < 2.0 l** | **Engines >= 2.0 l** |
| Reference | S | 28.0% | 28.0% | 0.0% | 0.0% |
| | M | 51.3% | 8.3% | 37.1% | 5.9% |
| | L | 20.8% | 0.7% | 11.0% | 9.0% |
| Free Play | S | 16.8% | 15.9% | 0.8% | 0.0% |
| | M | 56.4% | 8.7% | 40.5% | 7.2% |
| | L | 27.0% | 0.8% | 13.2% | 13.0% |
| Regulated Shift | S | 33.5% | 33.6% | 0.0% | 0.0% |
| | M | 53.9% | 13.1% | 36.7% | 4.1% |
| | L | 12.5% | 0.6% | 8.2% | 3.6% |

Both the car size and the technology mix differ in the three scenarios. Table 6 presents the resulting passenger car fleet development with regard to car size, applicable for all engine technologies on the left side. On the right side of Table 6, the distribution of engine size for gasoline and diesel engines is presented. In all scenarios, the mid-size category dominates. However, in the *Free Play* scenario a clear shift to larger cars and larger engines is visible. The S car segment nearly halves compared to the *Reference* scenario and the L segment increases by one third. The engines ≥2.0 l are even 35% above the *Reference* level. In the *Regulated Shift* scenario the tendency to downsize engines and vehicles is clearly visible. Small cars are 20% and engines <1.4 l nearly 30% above the *Reference* levels. The M size categories are elevated in both, the *Free Play* and the *Regulated Shift* scenarios, but numbers originating from the S or the L category respectively.

Table 7 and Table 8 present the development of tank-to-wheel emission factors for cars by category for the three underlying scenarios. In the case of air pollutants, specific emissions from gasoline and diesel engines are nearly the same in all three scenarios because of identical assumptions regarding emission limits, although car segment and size shares are different. The final scenario-based $CO_2$ emission factors per vehicle are a combination of technological progressions in energy efficiency and in case of hybrid vehicles the increase of the electric mileage due to higher battery capacities and again increase in energy efficiency.

Due to technology improvements, the $CO_2$ and pollutant emissions of conventional vehicles will already decrease in all scenarios for 2040 compared to 2010. A further reduction is achieved through an increasing share of electric driving in particular in the *Regulated Shift* scenario. Political $CO_2$ targets directly affect the achieved energy and thus $CO_2$ efficiency of the vehicles. The *Free Play* scenario with the least strict regulations consequently shows the highest emissions of the three scenarios except for PHEVs. This vehicle type shows a higher degree of maturity in this scenario as more PHEVs are demanded by the market, considering also the higher overall numbers of passenger cars in the *Free Play* scenario. The revers mechanism applies for the conventional gasoline vehicles, despite of stricter $CO_2$ targets in the *Regulated Shift* scenario. $NO_x$ emissions remain high for vehicles using a diesel engine, both in the case of conventional and hybrid electric vehicles (Table 8). Thus the $NO_x$ emission factors for an average diesel car remain approximately seven times higher compared to gasoline cars.

*Table 7: Tank-to-wheel $CO_2$ emissions in g/km of considered vehicle categories (G = gasoline, D = diesel, G-HEV = gasoline-hybrid vehicle, D-HEV = diesel-hybrid vehicle, PHEV = plug-in-hybrid vehicle (gasoline) and CNG = compressed natural gas vehicle)*

| Drive-train | Base year 2010 | Reference 2040 | Free Play 2040 | Regulated Shift 2040 |
|---|---|---|---|---|
| G | 197 | 127 | 148 | 131 |
| D | 184 | 114 | 125 | 111 |
| G-HEV | - | 87 | 117 | 94 |
| D-HEV | - | 69 | 79 | 88 |
| PHEV | - | 27 | 28 | 32 |
| CNG | - | 120 | 123 | 113 |

*Table 8: Tank-to-wheel $NO_x$ , CO, and PM emissions for different drive-train types in the reference scenario. (G = gasoline, D = diesel, G-HEV = gasoline-hybrid vehicle, D-HEV = diesel-hybrid vehicle, PHEV = plug-in-hybrid vehicle (gasoline) and CNG = compressed natural gas vehicle)*

| Drive-train | $NO_x$ [g/km] | | CO [g/km] | | PM [g/km] | |
|---|---|---|---|---|---|---|
| | 2010 | 2040 | 2010 | 2040 | 2010 | 2040 |
| G | 0.167 | 0.020 | 1.206 | 0.638 | 0.003 | 0.002 |
| D | 0.641 | 0.150 | 0.051 | 0.028 | 0.021 | 0.002 |
| G-HEV | - | 0.017 | - | 0.500 | - | 0.002 |
| D-HEV | - | 0.135 | - | 0.010 | - | 0.002 |
| PHEV | - | 0.003 | - | 0.009 | - | 0.001 |
| CNG | - | 0.057 | - | 1.442 | - | 0.000 |

Table 9 provides the derived emission factors for electricity and fuel generation by scenario. The results for power generation vary significantly depending on the assumed supply structure and for transport fuels only slightly due to the underlying structure of oil product use and generation in the energy system. For the consideration of well-to-tank emissions of hydrogen, the emission factors from electricity generation are divided by the (loss) factor 0.7. In addition, well-to-tank emissions from the gas supply for CNG vehicles were estimated using the simple methodology described above. As a result, the specific emissions 0.5 g $CO_2$ per MJ (based on gas consumed), 2 mg $NO_x$ per MJ, 0.5 mg CO per MJ and 0.1 mg $PM_{10}$ per MJ are considered in all scenarios below.

The fleet-wide emissions are a result of tailpipe emissions (tank-to-wheel) and refinery emissions as well as the emissions originating from the electricity generation, used for transport purposes (well-to-tank).

*Table 9: Calculated well-to-tank emissions from energy supply per unit of electricity respectively oil product in g/MJ*

| **Specific emission** | **2010** | **Reference 2040** | **Free Play 2040** | **Regulated Shift 2040** |
|---|---|---|---|---|
| $CO_2$ | | | | |
| electricity (g/MJ) | 138.3 | 86.9 | 114.2 | 24.2 |
| transport fuels (g/MJ) | 4.6 | 3.7 | 3.6 | 3.8 |
| $NO_x$ | | | | |
| electricity (g/MJ) | 0.1175 | 0.0775 | 0.0922 | 0.0439 |
| transport fuels (g/MJ) | 0.0041 | 0.0036 | 0.0035 | 0.0029 |
| CO | | | | |
| electricity (g/MJ) | 0.0522 | 0.0381 | 0.0439 | 0.0264 |
| transport fuels (g/MJ) | 0.0004 | 0.0004 | 0.0003 | 0.0003 |
| $PM_{10}$ | | | | |
| electricity (g/MJ) | 0.0036 | 0.0027 | 0.0032 | 0.0012 |
| transport fuels (g/MJ) | 0.0007 | 0.0005 | 0.0005 | 0.0004 |

Taking the above described scenario effects into consideration, different shares of tank-to-wheel and well-to-tank vehicle emissions can be identified (Figure 1). Clearly, the higher the grade of electrification, the less $CO_2$ is emitted per km. Due to a higher share of renewable energy in the 2040 electricity mix in the *Regulated Shift* scenario, the BEV and PHEV vehicles have the highest $CO_2$ benefits of all considered vehicle types. The conventional technologies develop less efficiently in the *Regulated Shift* scenario, whose framework settings strongly support the evolution of highly electrified drive-trains. Therefore, the conventional and full hybrid vehicles develop more efficient in other frameworks like the *Reference* or *Free Play* scenarios.

In case of $NO_x$ emissions, diesel vehicles as well as the electricity production contribute most to the overall emissions. Gasoline cars have similar $NO_x$ emissions as BEVs or PHEVs. Nevertheless, tailpipe (tank-to-wheel) $NO_x$ emissions might have different (local) impacts on air quality and health than $NO_x$ emissions from power plants. CO emissions remain an issue for gasoline and CNG vehicles in all scenarios, although, information on future emissions from CNG vehicles is highly uncertain. Particle emissions are critical both from indirect and direct sources and in this case, fuel production (gasoline and diesel) has considerable impact with the exception of CNG vehicles. Even in a predominantly renewable electricity supply, particle emissions are still clearly present, which is due to the emission estimate for the mostly decentralised use of biomass.

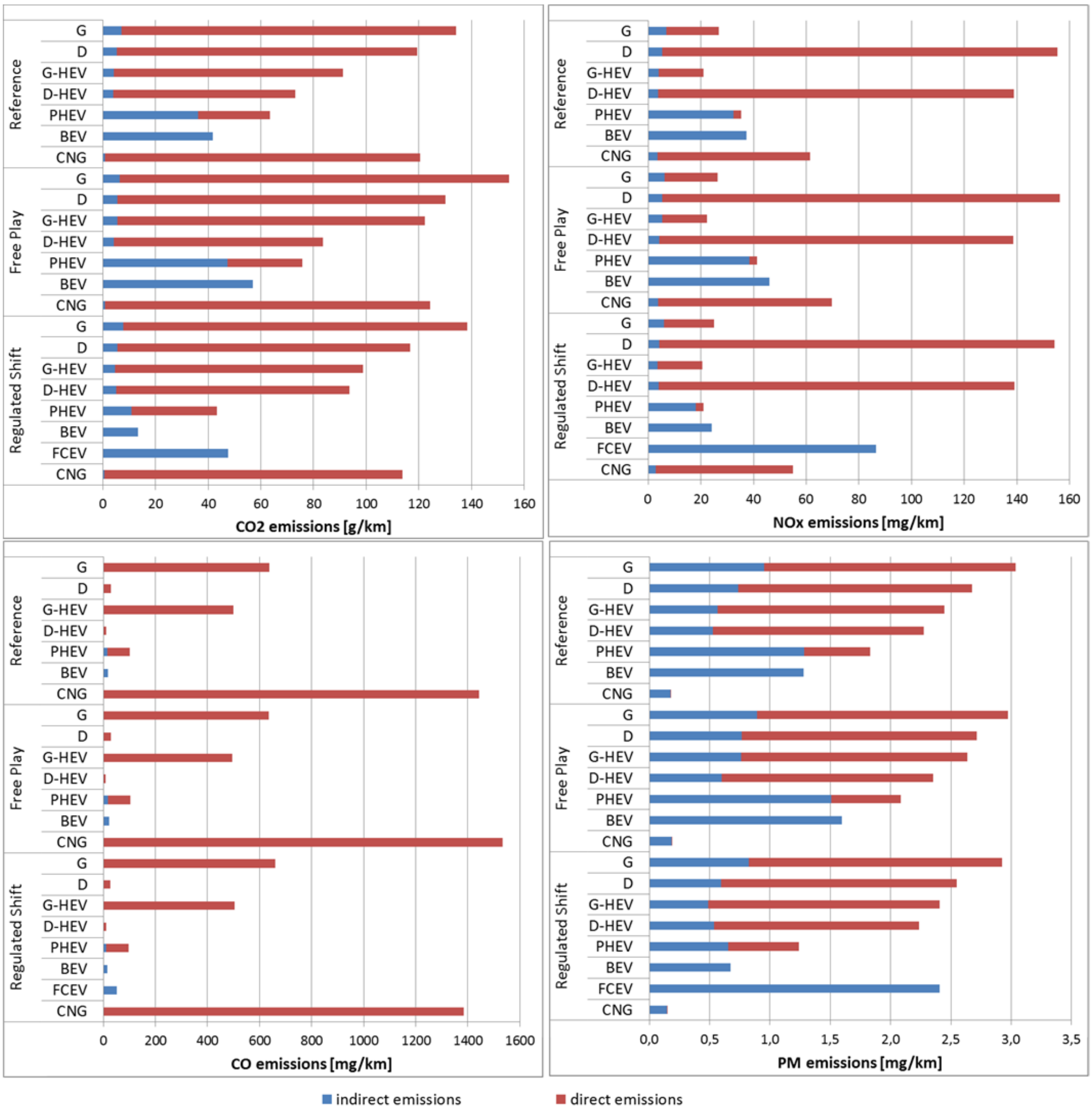

*Figure 1: Calculated total indirect and direct emissions of the vehicle technologies in 2040. (G = gasoline, D = diesel, G-HEV = gasoline-hybrid vehicle, D-HEV = diesel-hybrid vehicle, PHEV = plug-in-hybrid vehicle (gasoline), BEV = battery-electric vehicle, FCEV = fuel-cell electric vehicle and CNG = compressed natural gas vehicle)*

## 5. Conclusion

This paper highlights the importance to systematically address interdependencies of developments in the transport and energy sectors in scenario analysis, with regard to the overall emissions. The development of emission factors must take those interdependencies into account and future analyses need to build on plausible and consistent assumptions. Consistency and plausibility is best achieved in explorative scenarios, with a subsequent modelling of the effects of societal decisions on the transport and energy system. Development pathways into the future will influence car fleets, technologies and also the whole energy system. Important factors are changes in fleet composition and vehicle sizes, the market penetration of new vehicle concepts and technologies and also the future generation mix for electricity. One example of interdependence is the accelerated progress and efficiency improvements when more vehicles of an advanced technology enter the market. While general improvements can be expected with all technologies, the technologies with significant market shares will be able to improve faster than others.

The composition of vehicle fleets has a large impact on future emissions from passenger cars. For example, $CO_2$ emissions of gasoline vehicles vary by 17% and of diesel by 13%, purely due to differences in vehicle and engine size (see Table 7) While generally the electrification of private passenger cars is perceived as beneficial with regard to greenhouse gas emissions, the extent largely depends on the developments of the electricity system. The operational benefits alone are small, when electricity is not predominately generated by renewable sources and high share of coal based electricity is applied. Thus, a deep decarbonization pathway needs to include the electrification of significant portions of the passenger car fleets in conjunction with a sustainable power generation structure. In addition, temporal and regional interactions between energy and transport systems are relevant with regard to load balancing, resulting infrastructure needs and future energy costs and could also further improve the assessment of well-to-tank emissions.

Furthermore, the emission reduction prospects differ from pollutant to pollutant. For example, nitrogen oxide and particulate matter emissions from power generation could still significantly contribute in the future to the overall ambient air emissions, depending on the remaining thermal generation capacities for electricity. More precise bottom-up considerations of the role and emission factors of future decentralized biomass and biogas power plants are desirable in this respect. With regard to the direct tailpipe $NO_x$ emissions, a significant reduction is technically feasible and can be expected with all technologies. This inherits the assumption that the divergence between real-world driving emissions and test-bed emissions will diminish in the future. Furthermore, diesel fueled vehicles will have elevated tailpipe $NO_x$ emissions, albeit at much lower levels than today.

Further research is needed regarding the effects of different scenarios for ambient air quality. Since in some scenarios the release of air pollutants is shifted from tailpipe to power plant stacks, an effect of street-level emissions and imported background emissions can be expected. Furthermore, as tailpipe particulate emissions decrease, the secondary emissions from tire and break wear as well as from resuspension of dust become more important. This too warrants further research. Further research should also look into the life cycle aspects of fully electrified vehicles as well as resource aspects since the battery production is associated with high energy demand and emissions. Finally, the question on changes in the vehicle usage in light of emerging technologies should be investigated.

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## Appendix A: Supporting Information to:

# Well-to-wheel emission factors for future cars in Germany with a focus on fleet composition, new technologies and emissions from energy supplies

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Tables A1 to A4 contain the individual values of the bars in Figure 1 “Calculated total indirect and direct emissions of the vehicle technologies in 2040”. The following abbreviations are used:
G = gasoline vehicle
D = diesel vehicle
G-HEV = gasoline-hybrid vehicle
D-HEV = diesel-hybrid vehicle
PHEV = plug-in-hybrid vehicle (gasoline)
BEV = battery-electric vehicle
FCEV = fuel-cell electric vehicle
CNG = compressed natural gas vehicle

*Table A1: List of total indirect and direct $CO_2$ emissions [g/km] of the vehicle technologies in 2040*

| | **reference** | | **free play** | | **regulated shift** | |
|---|---|---|---|---|---|---|
| | indirect emissions | direct emissions | indirect emissions | direct emissions | indirect emissions | direct emissions |
| G | 7.05 | 126.96 | 6.44 | 147.69 | 7.81 | 130.55 |
| D | 5.44 | 113.96 | 5.51 | 124.55 | 5.67 | 110.98 |
| G-HEV | 4.66 | 87.06 | 5.90 | 116.82 | 4.64 | 94.11 |
| D-HEV | 4.14 | 69.24 | 4.61 | 79.37 | 5.09 | 88.61 |
| PHEV | 36.29 | 27.25 | 47.28 | 28.43 | 10.99 | 32.46 |
| BEV | 41.73 | - | 57.08 | - | 13.29 | - |
| FCEV | - | - | - | - | 47.64 | - |
| CNG | 0.88 | 119.56 | 0.93 | 123.25 | 0.73 | 113.02 |

*Table A2: List of total indirect and direct $NO_x$ emissions [mg/km] of the vehicle technologies in 2040*

| | **reference** | | **free play** | | **regulated shift** | |
|---|---|---|---|---|---|---|
| | indirect emissions | direct emissions | indirect emissions | direct emissions | indirect emissions | direct emissions |
| G | 6.86 | 20.00 | 6.26 | 20.00 | 5.96 | 19.00 |
| D | 5.30 | 150.00 | 5.36 | 151.00 | 4.32 | 150.00 |
| G-HEV | 4.07 | 17.00 | 5.32 | 17.00 | 3.54 | 17.00 |
| D-HEV | 3.78 | 134.98 | 4.20 | 134.43 | 3.88 | 135.25 |
| PHEV | 32.48 | 2.87 | 38.46 | 2.87 | 18.08 | 2.91 |
| BEV | 37.20 | - | 46.11 | - | 24.14 | - |
| FCEV | - | - | - | - | 86.52 | - |
| CNG | 3.50 | 58.00 | 3.70 | 66.00 | 2.90 | 52.00 |

*Table A3: List of total indirect and direct CO emissions [mg/km] of the vehicle technologies in 2040*

| | **reference** | | **free play** | | **regulated shift** | |
|---|---|---|---|---|---|---|
| | indirect emissions | direct emissions | indirect emissions | direct emissions | indirect emissions | direct emissions |
| G | 0.76 | 638.00 | 0.54 | 634.25 | 0.62 | 658.89 |
| D | 0.59 | 28.00 | 0.46 | 28.62 | 0.45 | 25.92 |
| G-HEV | 0.45 | 500.34 | 0.49 | 493.92 | 0.37 | 503.54 |
| D-HEV | 0.42 | 9.52 | 0.36 | 9.41 | 0.40 | 10.05 |
| PHEV | 15.35 | 85.71 | 17.67 | 86.41 | 10.19 | 86.45 |
| BEV | 18.27 | - | 21.94 | - | 14.51 | - |
| FCEV | - | - | - | - | 52.02 | - |
| CNG | 0.88 | 1442.00 | 0.93 | 1531.93 | 0.73 | 1383.25 |

*Table A1: List of total indirect and direct PM emissions [mg/km] of the vehicle technologies in 2040*

| | **reference** | | **free play** | | **regulated shift** | |
|---|---|---|---|---|---|---|
| | indirect emissions | direct emissions | indirect emissions | direct emissions | indirect emissions | direct emissions |
| G | 0.95 | 2.09 | 0.89 | 2.08 | 0.82 | 2.10 |
| D | 0.74 | 1.94 | 0.77 | 1.95 | 0.60 | 1.95 |
| G-HEV | 0.57 | 1.88 | 0.76 | 1.88 | 0.49 | 1.92 |
| D-HEV | 0.53 | 1.75 | 0.60 | 1.75 | 0.54 | 1.70 |
| PHEV | 1.28 | 0.55 | 1.51 | 0.58 | 0.65 | 0.59 |
| BEV | 1.28 | - | 1.60 | - | 0.67 | - |
| FCEV | - | - | - | - | 2.41 | - |
| CNG | 0.18 | 0.00 | 0.19 | 0.00 | 0.15 | 0.00 |