Article

Environmental Impact of Subsidy Concepts to Stimulate Car Sales in Germany

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Abstract: This paper establishes a prognosis of the long term environmental impact of various car subsidy concepts. The CO_2 emissions of the German car fleet impacted by the purchase subsidies are determined. A balance model of the CO_2 emissions of the whole car life cycle is developed. Consideration of production-, use- and End-of-Life processes are taken into account. The implementation of different subsidy scenarios directly affects the forecasted composition of the vehicle population and therefore the resulting life cycle assessment. All scenarios compensate the additional emissions required by the production pull-in within the considered period and hence reduce the accumulated CO_2 emissions until 2030. The exclusive funding of BEVs is most effective with a break-even in 2025.

Keywords: subsidy; automotive industry; prognosis; COVID-19; environmental impact; life cycle analysis

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1. Introduction

As a result of the containment measures against the Covid-19 pandemic, international vehicle sales collapsed dramatically in the first half of 2020. The German Association of the Automotive Industry (Verband der Automobilindustrie, VDA) predicts a decline of -23% of new passenger car registrations in Germany compared to the prior year [1]. With more than 800,000 employees and an annual turnover of 435 billion Euro in 2019, the German automotive industry is essential for prosperity and employment in Germany [2]. According to VDA president Hildegard Müller, the massively reduced production will lead to a decrease in employment [1].

From an economic point of view the Covid-19 pandemic shows some similarities to the 2008 financial crisis: at that time the passenger car registrations in Germany decreased to the lowest level since the German reunification. For the following year, the forecast without any car sales stimulation predicted 2.8 million new registrations, almost 0.3 million less than the already historically low number of 3.09 million new registrations in 2008.
In reaction, the German government decided to introduce a subsidy program in 2009, in which a purchase bonus for new cars could be earned if the old ones were scrapped. One target of the "environmental bonus" was to replace old cars with high specific emissions with new and more efficient ones. The government's goal was to reduce pollution and stimulate car sales at the same time. Thus, the number of new registrations in 2009 rose by 23.3% to 3.81 million vehicles and provided

according to Höpfner et al. [3] reduced pollution due to the rejuvenation of the German passenger car fleet.

Due to the renewed economic challenges as a result of the Covid-19 pandemic, a considerable number of voices from the automotive industry [4], automotive lobby [5] and parts of German politics [6] demands a subsidy concept similar to the 2009 introduced "environmental bonus". The scope of this potential subsidy has not yet been worked out. Unlike in 2009, electromobility has found its way into the automotive market and therefore specific fundings of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are conceivable to further reduce German car fleet emissions. Contrary to the concept proposed in this paper, existing subsidy concepts of electric and hybrid cars [7] do not require a replacement of conventional cars. An additional promising concept includes rewarding purchases of smaller vehicles.

The goal of this paper is a quantified evaluation of various subsidy concepts with regards to the ecological aspects, focusing on the CO_2 emissions. To provide a holistic view on the environmental impact of the various subsidy concepts, the cradle-to-grave life cycle including production, operation and End-of-Life (EoL) emissions are considered.

2. Literature Review

As presented in chapter 1 the financial crisis 2008 and the introduced car subsidy show some similarities to the current situation due to the Covid-19 pandemic.
The "environmental bonus" introduced in Germany has been analyzed extensively. Shortly after the "environmental bonus" has been introduced, Höpfner et al. [3] determined a positive ecological effect of the subsidy. Besides, they demonstrated that the CO_2 emissions of the pulled forward manufacturing were compensated after 6.000 km driving distance due to the reduced use phase emissions of the new cars.
Klößner et al. [8] examined the impact of European car scrappage programs on new vehicle registrations and respective CO_2 emissions. Using a multivariate synthetic control method with time series of economic predictors, they found that the German subsidy had a positive effect on stabilizing the car market. However, the economic benefit caused 2.4 million tons of additional CO_2 emissions according to their work.

Various economic examinations of the "environmental bonus" have been made. The micro- and macroeconomic effects of the "environmental bonus" have been investigated by Läufer et al. [9]. They concluded that the "environmental bonus" was not very effective but created macroeconomic stability.
Müller et al. [10] analyzed the impact of the subsidy on the overall car sales by using a dataset provided by the Organisation for Economic Co-operation and Development (OECD) of 23 countries and found a positive effect of car scrappage programs on overall car sales as long as the subsidy is in place.
The pull-forward effect of the German car scrappage scheme has been examined by Böckers et al. [11] creating a monthly dataset of new car registrations owned by private consumers. According to them, the small and upper small car segments have benefited specifically from the scrappage program, as they made up 84% of the newly registered cars during the program.

In response to the financial crisis, other countries besides Germany introduced a car subsidy program. The "Summary of the Consumer Assistance to Recycle and Save Act of 2009" (CARS) was launched in 2009 by the US government [12] and has been broadly reviewed. Lenski et al. [13] analyzed the net effect of CARS on greenhouse gas emissions from a full vehicle life cycle perspective. They found that CARS had a one-time effect of preventing 4.4 million metric tons of CO_2 eq. emissions,

about 0.4% of US annual light-duty vehicle emissions.
By comparing the predicted fuel economy without the existence of the program and the actual data, Sivak et al. [14] determined an improved average fuel economy of the US passenger car fleet in July and August 2009.
Li et al. [15] investigated the effects of the CARS program on new vehicle sales and the environment. By using Canada as the control group in a difference-in-differences framework, they determined that CARS increased new vehicle sales only by about 0.37 million during July and August of 2009, implying that approximately 45% of the spending went to consumers who would have purchased a new vehicle anyway. They calculated a reduction of the CO_2 emissions by 9–28.2 million tons.

In summary the literature shows disagreement about the environmental impact of the car subsidy in 2009 and does not answer whether a new subsidy would have a positive impact on the environment.

To the best of our knowledge, there is no study that predicts the environmental impact of a car subsidy that addresses the decrease of vehicles sales due to the Covid-19 pandemic. We perform a life cycle analysis of the German passenger fleet with a level of detail, which no previous study has shown.

3. Methodology

The model developed in this paper calculates the annual CO_2 emissions of the German passenger car fleet iteratively starting 2019. New registrations and decommissions of the present year lead to the fleet data of the subsequent year. For the baseline of the CO_2 emissions, the impact of the Covid-19 pandemic on the car sales profile is considered. Three different subsidy concepts are applied to the baseline scenario and variations of the CO_2 emissions are determined, respectively.

3.1. Scope

To analyze the environmental impact of various subsidy concepts, the full life cycle of passenger cars is taken into account. Therefore, temporal and geographical system boundaries must be defined. To predict the long term impact the time period covers the years 2019 to 2030. Due to the rapid technological progress the reliability of the predicted data after 2030 decreases significantly.

As effects that extend beyond the national borders are subject to large uncertainties, the system boundary is drawn around Germany. After deregistration from the German transport system only the EoL (decommissioning) emissions and no further driving performances will be accounted for in the life cycle analysis, as shown in Figure 1.

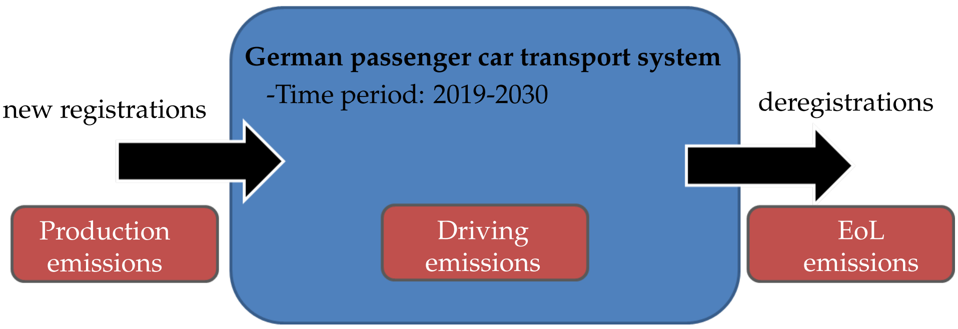

Figure 1. System boundaries

The car population is categorized into two main attributes: segment and drive train technology. The segment categorization is based amongst other parameters on the weight and size of the vehicle, following the Federal Motor Transport Authority (Kraftfahrtbundesamt, KBA) clustering method [16]. In this work, we use an English translation of the segment names as used by the KBA (Table 1).

Table 1. Segments translation

Segment name according to KBA [16]	English segment name
Minis	mini class
Kleinwagen	small class
Kompaktklasse	compact class
Mittelklasse	middle class
Obere Mittelklasse	upper middle class
Oberklasse	upper class
Sport Utility Vehicles (SUVs)	Sport Utility Vehicles (SUVs)
Mini-Vans	mini vans
Großraum-Vans	large vans
Sportwagen	sports cars
Geländewagen	off-roaders
Wohnmobile	caravans

In this analysis, there is no consideration of the segments sports cars and caravans. This is explained with their exclusive use for recreational or leisure purposes which makes the expenditure of public funds for these vehicles not justifiable. Furthermore, commercial vehicles like trucks are excluded since the subsidy presented here is focused solely on private customers. Finally, off-roaders are excluded as they are used either commercially (e.g. forestry) or for leisure purposes. This limits the scope to 84% of the whole German passenger car population.
Further we focus only on the drive train technologies gasoline, diesel, electric and plug-in hybrid. In this context, the plug-in hybrid vehicle contains a gasoline engine and an electric drive train.

3.2. Current Vehicle Distribution

At first, a model is defined which describes the German passenger car population for the next ten years. Therefore, 2019 is considered as a baseline with real data. From 2020-2030 we take recourse to prognosis data as shown in section 3.3.

To obtain a sufficient data set for the 2019 baseline, the vehicle data from the 2017 "Mobility in Germany" (Mobilität in Deutschland, MID) study by the German Federal Ministry of Transport and Digital Infrastructure [17] are categorized into segments and drive train technologies according to 3.1. Given the negligible average vehicle age change from 2017 to 2019 of 0.2 years [18], we assume that the overall age distribution of the German vehicle stock did not change significantly. Therefore, a linear transformation of the 2017 data is made to obtain the age distribution of the segments in 2019. Figure 2 presents the resulting age distribution of the German passenger car fleet.

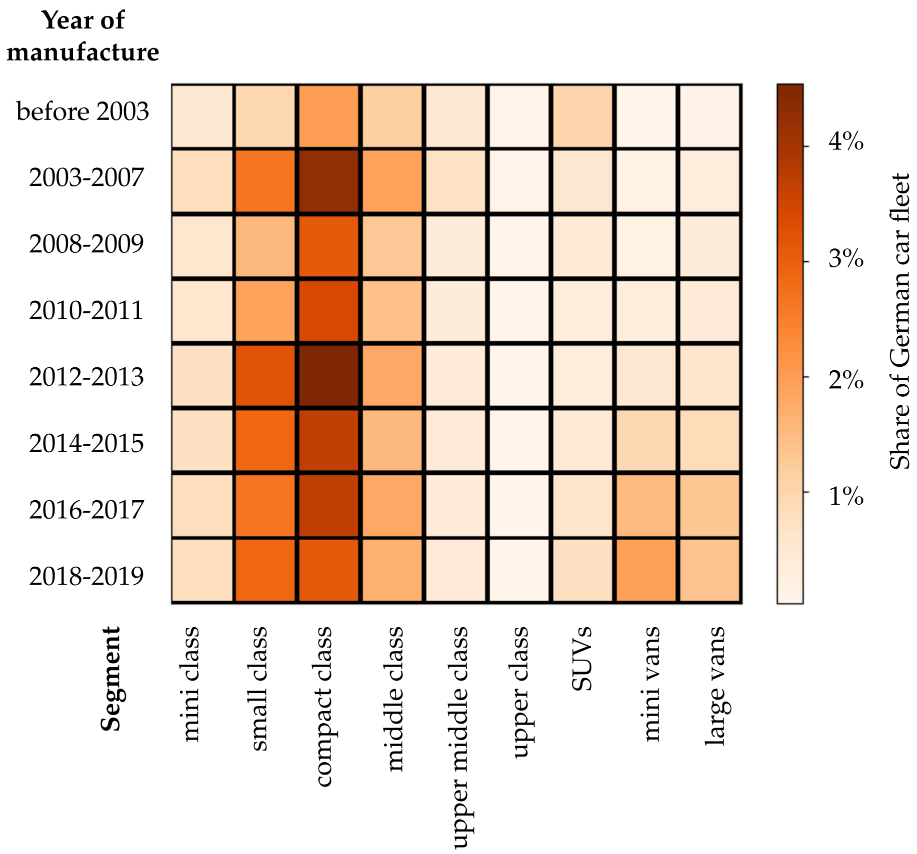

Figure 2. Age distribution of German vehicle fleet 2019

The same data is also available for the vehicle drive train technology and is linked with the year of manufacture and the segment category.
Combined with the number of total vehicle stock [19] the baseline for 2019 is built.

3.3. German Car Population Development until 2030

In order to predict the car population until 2030, estimations for new registrations and deregistrations must be made.

New Passenger Car Registrations

To determine new passenger car registrations the total number and their distribution into the categories as defined in 3.1 are needed. The annual number of new registrations and their classification regarding the drive train technology is obtained from the "proKlima" scenario of Agora 2018 [20] (Figure 3).

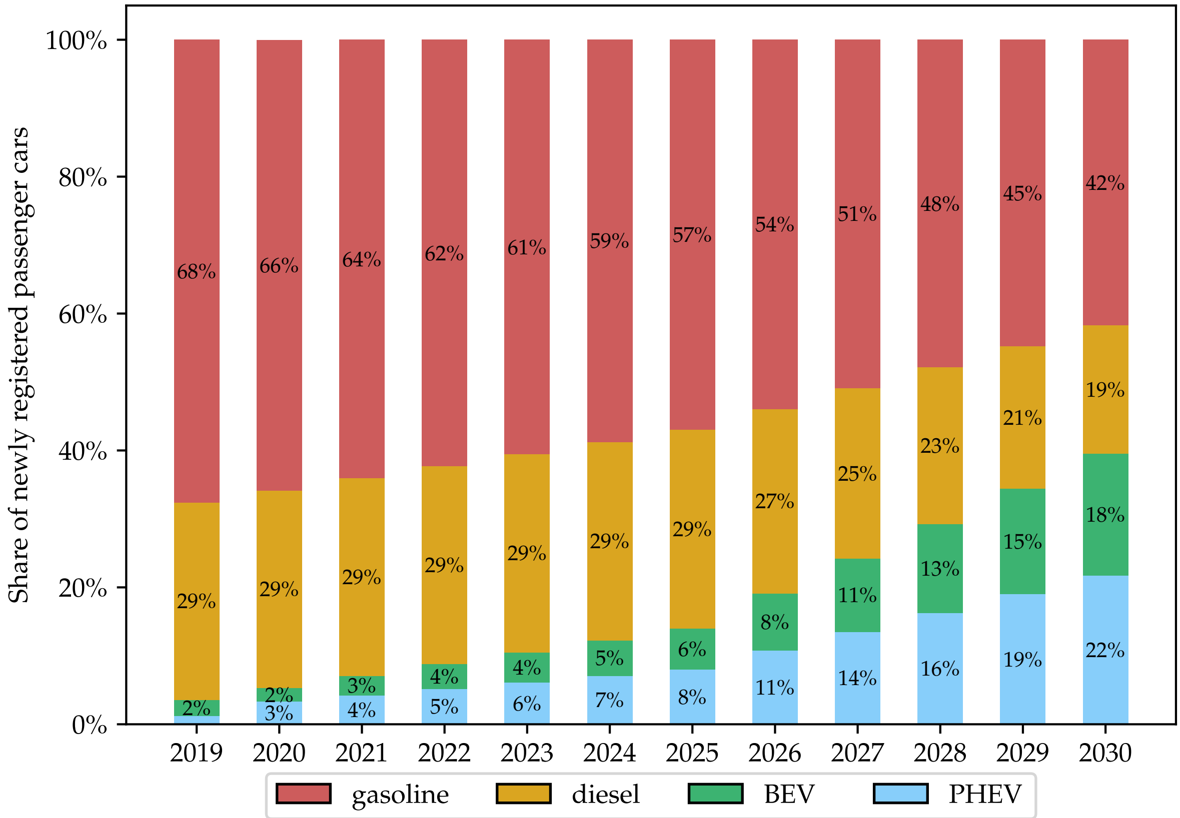

Figure 3. Linear interpolation of "proKlima" drive drain technology scenario

Additionally, an estimation concerning the segments is created based on the trend of the new registration numbers from previous years. For the segments large vans, mini vans, upper class, and upper middle class, we assume that the share of new registrations remains constant. In addition, we assume that the new registration share of segments not considered in this analysis will stay constant, which results in a non-varying share of the overall scope of 82%.

A noticeable growth of the Sport Utility Vehicle (SUV) segment is observed during the last years [21].

This trend is expected to continue and is anticipated to reach an annual new registration share of 40% in 2030. Since this value is based on an assumption a sensitivity analysis is performed in 4.4.2.

The growth in the SUV segment is subtracted proportionally from the other segments depending on their share in the reference year 2019. The share of large vans and mini class segments are not modified as customers are unlikely to change to an SUV due to the completely different usage profiles.

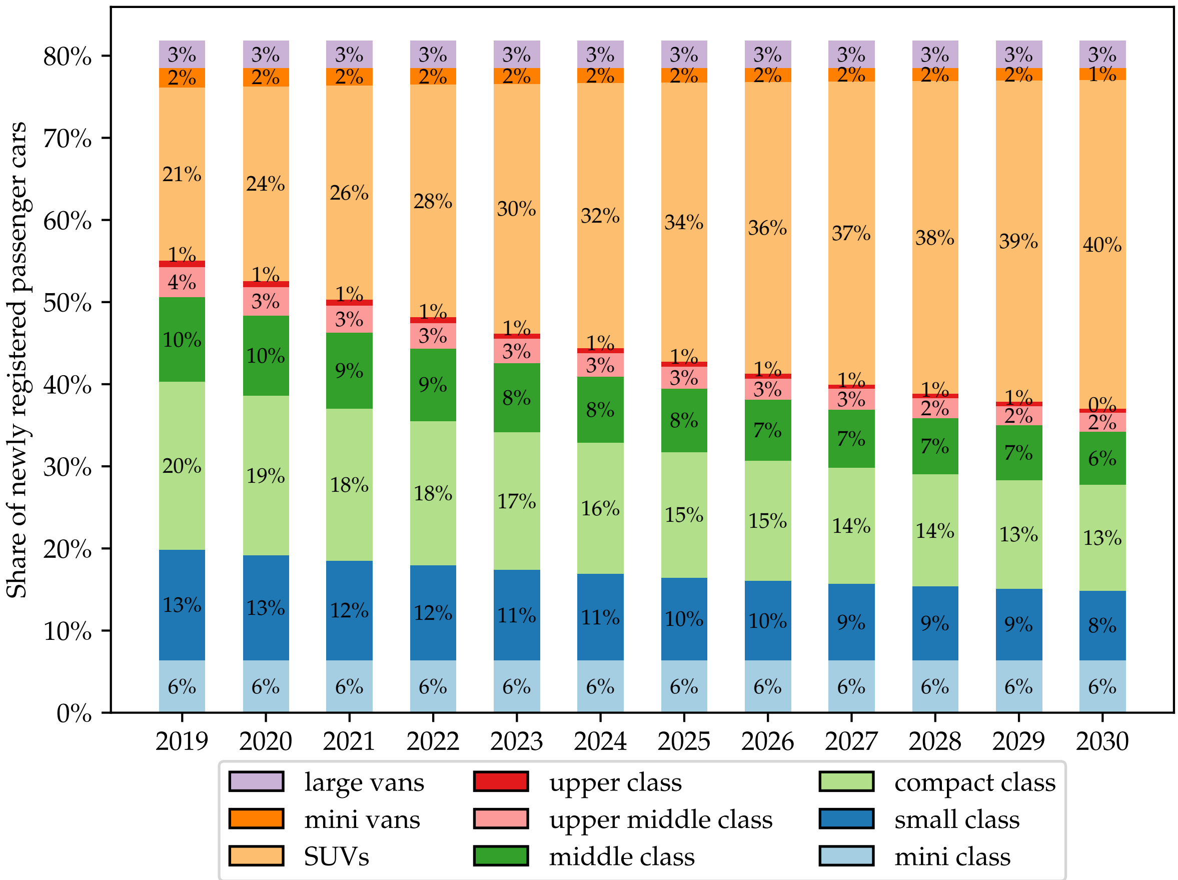

Figure 4. Segment scenario

Vehicle disposal

In this analysis we assume that every vehicle which is deregistered from the German transport system as defined in 3.1 will immediately get disposed, meaning scrapped or recycled. As usage profiles of exported vehicles are unknown the vehicles are disposed simultaneously with their deregistration in this model.

In the last four years a consistent age-dependent deregistration trend can be seen in Figure 5. Therefore, the future deregistration rates are assumed to be identical to 2019. The peak after three years can be explained by the end of many leasing contracts, which can contribute to exportation of vehicles. Additionally, the first legally required technical inspection ("Hauptuntersuchung", HU) of the vehicles and the associated phasing out of early defective vehicles takes place in this period. This might add to the observed peak. The peaks that occur every two years, especially for older vehicles, are also due to the interval of the mandatory technical inspections in Germany. As technical defects are detected and repairs may become necessary, it is often cheaper to scrap or export the vehicles than to continue their operation.

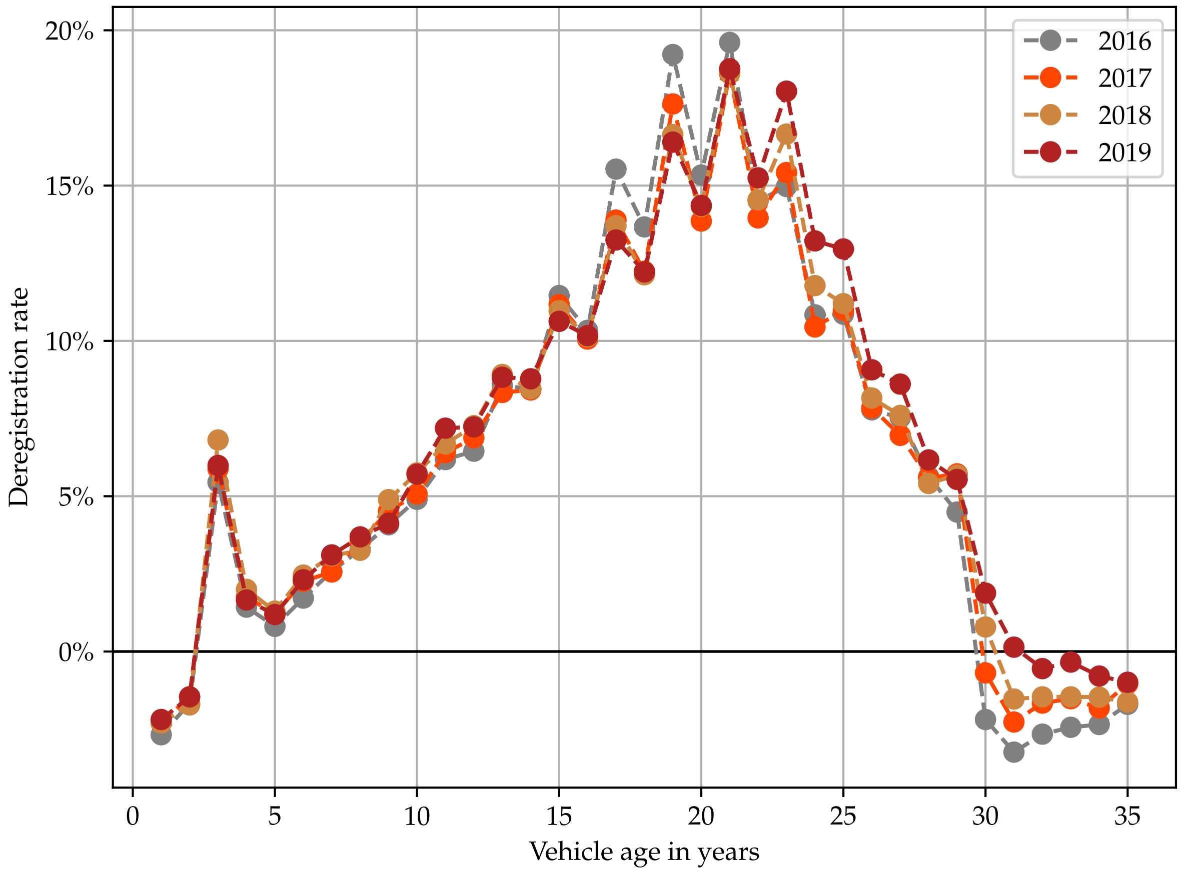

Figure 5. Age dependent deregistration data 2016-2019 (based on [22])

As explained in section 3.4, vehicle production is modeled separately from deregistrations and only for new vehicles. The negligible number of new registrations (negative deregistration) for very old vehicles (probably as vintage vehicles) is ignored.

3.4. Modeling car population development

The development of the car population for different scenarios is calculated using an iterative deregistration and production process. In the first step, the vehicle population (starting with the 2019 population from [22]) for each year of manufacture is reduced according to the deregistration rate for the respective age. Subsequently, the age groups are shifted back one year and the vehicle production of the considered year is set to maintain a constant total vehicle population. The vehicle deregistration rate is scaled from the real data shown in Figure 5 in order to match the prognosis of newly registered cars between 2020 and 2030 and of the "proKlima" [20] scenario.

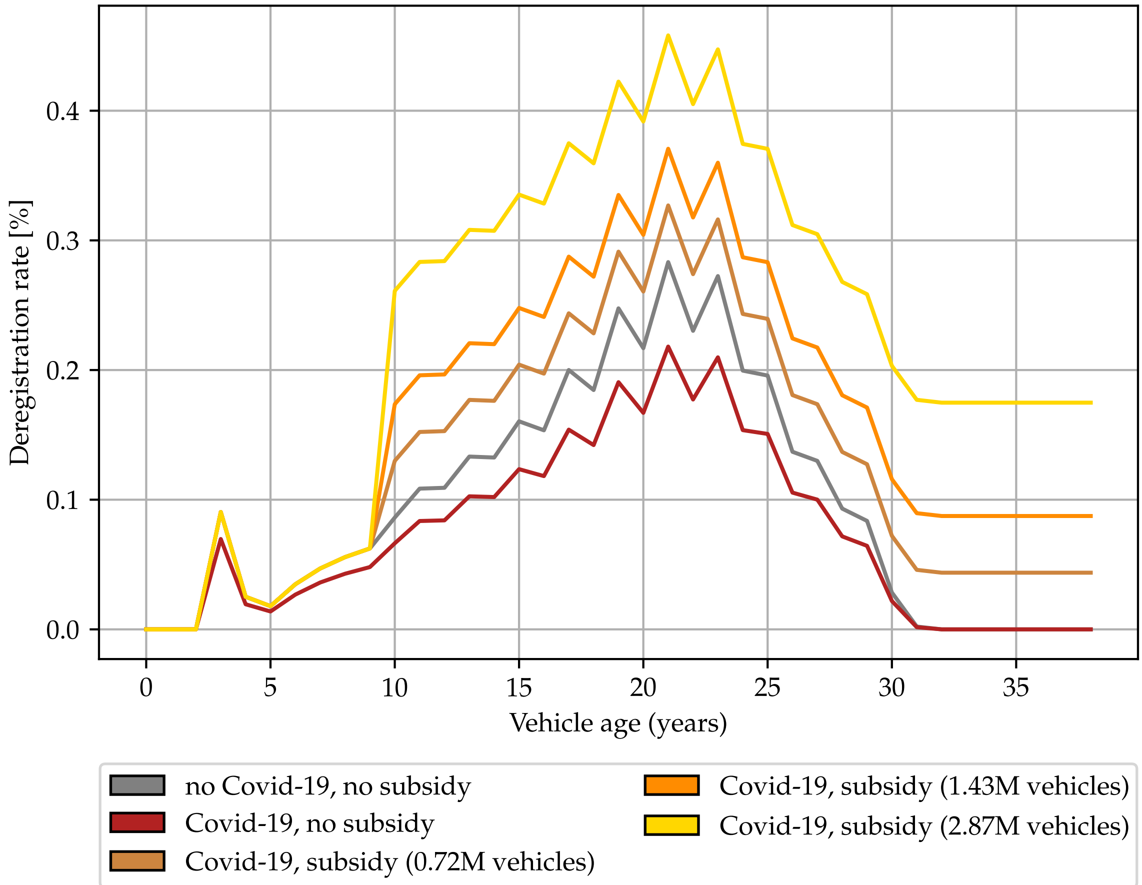

Figure 6. Deregistration rate distributions of different scenarios

In the next step, the modified scenarios (shown in Figure 6) are derived from the baseline by adapting the deregistrations only. First, the deregistration rate is decreased to reflect the reduced registrations due to owners financial uncertainty during the Covid-19 pandemic. The total vehicle registrations in 2020 are decreased by 23% compared to 2019 [1]. To simulate a subsidy in 2021, the deregistration of vehicles older than 10 years is increased to match the total number of subsidized vehicles. For the baseline scenario this number is set to the predicted new registration decrease due to the Covid-19 pandemic (0.72 million). In 4.4 we discuss the impact of the number of subsidized cars, therefore an additional analysis of twice and four times the baseline amount (1.43 and 2.87 million) are made.

This approach considers the reduced vehicle production in subsequent years after the subsidy is introduced (pull-out effect) and the increased total vehicle production due to early deregisterations compared to a scenario without a subsidy.

Figure 7 shows the annual and the accumulated vehicle registrations for different scenarios. The economic uncertainty due to the Covid-19 pandemic reduces the total number of vehicle registrations by forcing owners to keep their vehicles longer. Contrary, the subsidy leads to earlier replacements and therefore increases the new registrations. As already explained for Figure 5, there is a first peak of vehicle decommissioning after three years.

This can be seen also in the new registrations, as the additional vehicles produced due to the subsidy also lead to an increased number of vehicles being taken out of service three years after the subsidy. In turn, this leads to an increase in new purchases which can be seen four years after the subsidy. This time delay is due to the fact that we model the transition from one year to the next and thus the age of the vehicles in the previous year are taken into account for the scrapping and new purchases in the year under consideration.

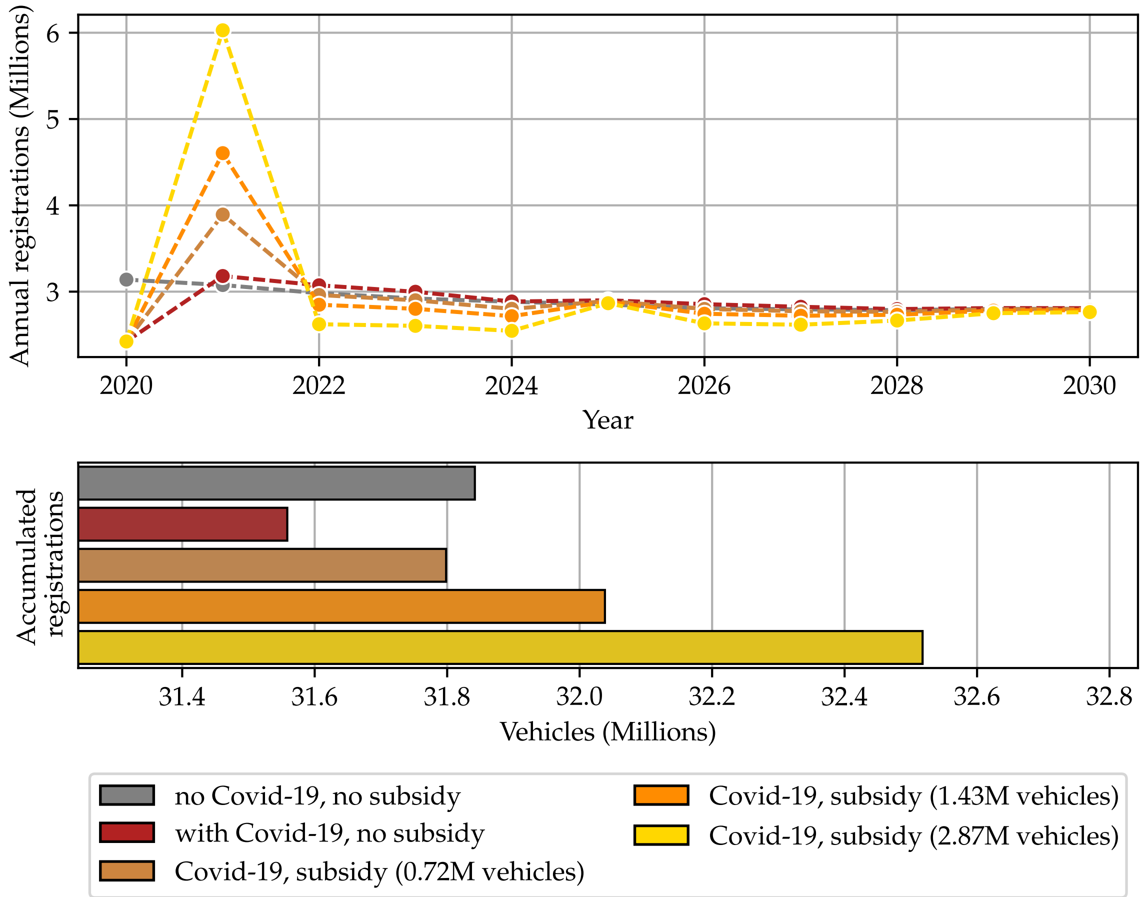

Figure 7. Annual and accumulated vehicle registrations

3.5. Life Cycle Emissions

To perform a cradle-to-grave life cycle analysis the production, use, and EoL phases are considered. The focus is primarily on the calculation of greenhouse gas emissions (CO_2 equivalent emissions, 20 year Global Warming Potential (GWP 20)). In this analysis, the direct CO_2 emissions of the combustion engines in the use phase are set identical to their CO_2 equivalent emissions.
The amount of production and EoL emissions are assumed to be constant for the upcoming years. They are only dependent on the segment and power train type of the vehicle and not changing with the production and disposal date.

In order to analyze the life cycle emissions of the drive train technologies per segment, specific input data (weight, direct CO_2 emissions, fuel, and electric energy consumption) is needed. Complete data for gasoline and diesel vehicles is available. For PHEVs and BEVs the required input is derived from defined reference vehicles. Currently, in some segments there are no vehicles available. In these cases input data are interpolated from adjacent segments.

3.5.1. Production

All production analyses are performed with the Ecoinvent 3.5 database [23]. The cutoff allocation is used and all location settings are set to global.

Petrol and Diesel

To perform a life cycle analysis for gasoline and diesel vehicles, the curb weight is used as the input value (Table 2).

Table 2. Weight distribution of vehicles with a combustion engine [24]

Segment	Curb weight [kg]
mini class	1038
small class	1191
compact class	1389
middle class	1617
upper middle class	1831
upper class	2035
SUVs	1506
mini class-Vans	1514
large vans	1754

It is assumed that there is no curb weight difference between gasoline and diesel vehicles. The emissions are calculated with the processes *passenger car production, gasoline* and *passenger car production, diesel* in Ecoinvent. To consider production only, the Ecoinvent data (flow) *manual dismantling of a used passenger car with internal combustion engine* is excluded.

Battery Electric Vehicle (BEV)

In order to perform the production analysis of the BEVs, the curb weight is divided into the battery weight and the remaining vehicle weight. The battery weight is calculated based on the battery capacity. Therefore, a constant energy density for all BEVs is defined.

A representative energy density at a battery packaging level is defined by averaging the values of the VW E-golf (113 Wh/kg) [25] and the 2017 Tesla Model S P100D (160 Wh/kg) [26]. This results in an energy density of 136 Wh/kg which is used to calculate the battery weight of all BEVs based on the battery capacity. For each segment, a reference BEV is defined based on the number of newly registered vehicles in 2019 [27] (Table 3). In the SUV segment the Hyundai Kona Electro and the Audi E-Tron both nearly have the same registration numbers in 2019. Since the share of compact SUVs is expected to continue growing ([27], the Hyundai Kona Electro is chosen as the reference model.

Table 3. Weight distribution of BEV

Segment	Curb weight [kg]	Battery capacity [kWh]	Battery weight [kg]	Remaining curb weight [kg]	Reference
mini class	1095	17.6	129	966	smart EQ fortwo. [28]
small class	1345	42	308	1037	BMW i3 [29]
compact class	1545	40	293	1252	Nissan Leaf [30]
middle class	1611	55	404	1207	Tesla Model 3 [31]
upper middle class	-	-	-	-	-
upper class	2290	100	734	1556	Tesla Model S [31]
SUVs	1593	39	288	1305	Hyundai Kona Elektro [32]
mini vans	1610	39	288	1322	Kia e-soul [33]
large vans	-	-	-	-	-

The emitted emissions from the BEV battery pack production are determined with the process *battery production, Li-ion, rechargeable, prismatic*. This process also considers the transportation of the single cells from Peking to Amsterdam by ship and a 1000 km transportation route within Europe by truck.

For the remaining electric vehicle the process *passenger car production, electric, without battery* [34] is used with the remaining curb weight from Table 3.

Plug-in Hybrid Electric Vehicle (PHEV)

In this analysis the PHEV is a combination of a conventional and an electric vehicle. Therefore, the PHEV consists of a battery, electric power train components, and the remaining vehicle, which contains all components of the combustion power train. This analysis is based on manufacturer's data from reference vehicles (Table 4).

Table 4. Manufacturer's data of PHEVs

Segment	Curb weight [kg]	Battery capacity [kWh]	Maximum power of electric drive train [kW]	Reference
mini class	-	-	-	-
small class	1660	7.6	65	Mini Cooper SE Countryman [35]
compact class	1750	8.8	65	BMW 225xe Active Tourer [36]
middle class	1780	9.8	50	Kia Optima Plug-In Hybrid [37]
upper middle class	1910	11.2	62	BMW 530 e [38]
upper class	2170	14.1	100	Porsche Panamera 4 E-Hybrid [39]
SUVs	1971	13.8	70	Mitsubishi Outlander [40]
mini vans	1725	15.6	75	Mercedes B 250 e [41]
large vans	-	-	-	-

Similar to the BEV batteries, the PHEV battery weight is calculated based on the battery capacity with a constant energy density for all types of plug-in vehicles. We consider all batteries at the packaging level. Since the PHEV batteries are significantly smaller than the BEV ones, an assumption of the same energy density is not suitable.
Therefore, the mean value of the energy densities of the Kia Optima (75 Wh/kg) [37] and the Mercedes B 250 e (104 Wh/kg) [42] of 89,5 Wh/kg is assumed for all PHEVs.
In addition, the electric power train components such as an electric motor, a charger, and cables are considered. Due to lacking data on the actual weight of these components, the weight is scaled with the maximum power of the electric power train. In this analysis, the baseline is made according to the default value in Ecoinvent of a 100 kW power train with a weight of 70 kg. The resulting parameters (Table 5) are used in Ecoinvent for the production analysis.

Table 5. Calculated weight distribution of PHEVs

Segment	Remaining curb weight [kg]	Battery weight [kg]	Electric power train weight [kg]	Reference
mini class	-	-	-	-
small class	1525	85	50	Mini Cooper SE Countryman [35]
compact class	1601	99	50	BMW 225xe Active Tourer [36]
middle class	1632	110	39	Kia Optima Plug-In Hybrid [37]
upper middle class	1724	125	50	BMW 530 e [38]
upper class	1935	158	77	Porsche Panamera 4 E-Hybrid [39]
SUVs	1763	154	54	Mitsubishi Outlander [40]
mini vans	1393	174	58	Mercedes B 250 e [41]
large vans	-	-	-	-

For the Battery pack production of the PHEVs, the same method as used for the BEVs is applied. The process *electric motor production, vehicle* is used to determine the emitted emissions to produce the components of the electric power train.

The remaining part of the vehicle is assumed to be a gasoline engine car. Therefore, the process *passenger car production, petrol* is applied to analyze the production.

3.5.2. Use Phase

The emitted emissions during the use phase are composed of the emissions based on fuel and electric energy consumption, the well-to-tank emissions, and the emissions due to maintenance of the vehicle and the road infrastructure.
In 2019 the average annual mileage of passenger cars was 13.602 km [43]. In this model, it is assumed, that in the future every car will have the 2019 average annual mileage.

Combustion Engine Vehicles

The use phase emissions of the gasoline- and diesel-powered vehicles are dependent on the vehicle's segment and age. Based on these criteria, the KBA [44] provides a database of the average direct CO_2 emissions and fuel consumption which are displayed in the supplementary materials in Table S1. In this work, they are assumed to be identical to the CO_2 equivalent emissions.

Battery Electric Vehicle (BEV)

In this analysis, the BEVs are causing indirect CO_2 emissions because of their consumed electric energy during the use phase.
For each segment, a reference BEV is defined based on the number of newly registered vehicles in 2019 [27]. If a model in this segment would have a dominant share of the newly registered cars, it is considered as the reference BEV. Otherwise, the two models with the highest number of newly registered vehicles in the segment are selected and a weighted average of the energy consumption (weight factor) according to their new registration numbers is built (Table 6).

Table 6. Energy consumption of BEVs

Segment	Reference model	Energy consumption [kWh/100 km]	Weight factor	Weighted average energy consumption [kWh/100 km]
mini class	smart EQ fortwo. [28]	14.0	1	14.0
small class	BMW i3 [29]	13.1	0.66	14.5
	Renault Zoe [45]	17.2	0.34	
compact class	VW E Golf [46]	12.9	0.64	14.4
	Nissan Leaf [30]	17.1	0.36	
middle class	Tesla Model 3 [31]	16.0	1	16.0
upper middle class	-	-	-	-
upper class	Tesla Model S [31]	19.0	1	19.0
SUVs	Hyundai Kona Electro [32]	15.0	0.51	18.6
	Audi E-Tron [47]	22.4	0.49	
mini vans	Kia e-soul [33]	15.6	1	15.6
large vans	-	-	-	-

In 2019, there have not been any BEVs newly registered in the segments upper middle class and large vans. Since the market for electric vehicles will grow [20], we assume that future electric vehicles will also be available in these segments. Based on the curb weight of the combustion engine vehicles, we estimate that upper middle class and large vans have the same energy consumption. The electric energy consumption of upper middle class is assumed as an average of middle class and upper class.

Plug-in Hybrid Electric Vehicle (PHEV)

To determine comparable CO_2 emissions from plug-in hybrids, a combination of the direct exhaust emissions and the energy consumption of the electric drive train is made (Table 7).
The manufacturer's data for the reference vehicles either rely completely on the New European Driving Cycle (NEDC) or were measured with the Worldwide harmonized Light vehicles Test Procedure (WLTP) and was transferred back to the NEDC. The NEDC considers half of the driving cycle using the combustion engine and the other half using the electric power train. In this data, the electric energy consumption is considered emission-free. In order to correct this effect, we add the appropriate indirect emissions for electric power consumption.

Table 7. CO_2 Emissions and energy consumption of PHEVs

Segment	CO_2 emissions (combined) [g/km]	Fuel consumption [l/100km]	Energy consumption [kWh / 100 km]	Reference model
mini class	-	-	-	-
small class	45	2,0	14.0	Mini Cooper SE Countryman
compact class	42	1.9	13.5	BMW 225xe Active Tourer
middle class	37	1.6	12.2	Kia Optima Plug-In Hybrid
upper middle class	42	1.8	14.8	BMW 530 e
upper class	62	2.7	16.1	Porsche Panamera 4 E-Hybrid
SUVs	40	1.8	14,8	Mitsubishi Outlander
mini vans	32	1.4	14.7	Mercedes B 250 e
large vans	-	-	-	-

Indirect Emissions

In this model the consumed electric energy causes indirect emissions based on the specific carbon dioxide emissions of the German electricity mix. In 2020 the generation of one kWh electric energy is prognosed to cause 432 g CO_2 eq. emissions [48].
Pehnt et al. [48] calculate 318 g CO_2 eq. emissions for the electricity mix in 2030, the value here decreases linearly for the years 2020 to 2030. The Well-to-Tank factors are used to determine the upstream emissions of consuming fuel. Here, Schallaboeck et al. [49] stated 685 g resp. 408 g CO_2 equivalent emissions to produce one liter gasoline resp. diesel. The data for the fuel consumption are displayed in the supplementary materials in Table S2. All PHEVs are assumed to have a gasoline engine.

Maintenance

During the use phase, the replacement of vehicle spare parts and the maintenance of the road network is considered. To calculate the vehicle maintenance the flow *passenger car maintenance* is used in Ecoinvent and is adapted according to the vehicle's weight and power train type [50]. We follow the same approach as in Agora 2019b [51] "basic scenario" and assume for each vehicle a lifespan of 150 000 km and do not consider any battery exchange for BEVs and PHEVs.
In order to determine the maintenance of the road network the flow *road maintenance* is used. This introduces a weight-dependent contribution during the use phase.

3.5.3. End-of-Life

In this model, it is assumed that every deregistered vehicle is eventually disposed. The equivalent CO_2 emissions due to this process are determined in Ecoinvent using the flows *manual dismantling of used passenger car with internal combustion engine*, *treatment of used glider, passenger car, shredding*, *treatment of used internal combustion engine, shredding*, *treatment of used powertrain for electric passenger car, dismantling* and *market for used Li-ion battery* according to [34].

3.6. Subsidy Concepts

Three subsidy concepts are introduced in this chapter. They reflect aspects of the current discussions about the possible subsidy scope. Höpfner et al. [3] showed, that 84% of the subsidy from the "environmental bonus" in 2009 was used to purchase small cars (mini class, small class, and compact class). Therefore, 84% of all new registrations due to the subsidy will happen in the categories mini class, small class, and compact class. For this distribution, the predicted new car registration shares for 2021 are used. All segment shares are evenly scaled in order to reach 84% share in the small cars category. The impact of this effect is discussed in 4.4.1.

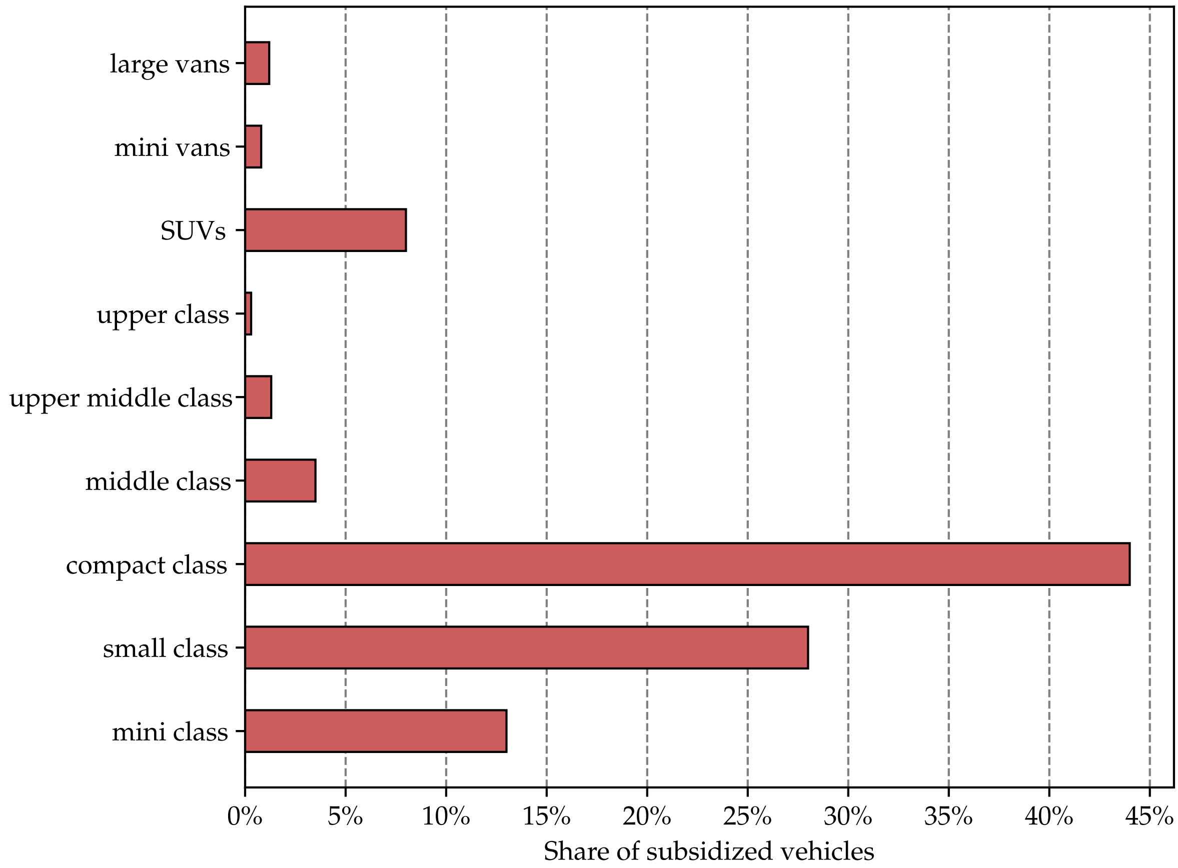

Figure 8. Subsidized vehicles distribution of "broad funding" concept

The distribution shown in Figure 8 is used as a baseline for all subsidy concepts. In 4.4.1 the influence of this distribution is discussed.
Similar to the "environmental bonus" in 2009 a mandatory requirement to earn the subsidy is a minimum vehicle age (in this case 10 years).

"Broad Funding" Concept

In this concept, the subsidy is not restricted to a certain vehicle type. Except for the higher demand in mini, small, and compact class segments, the same composition of the newly registered cars as predicted without the subsidy will occur. The subsidy only increases the total number of newly registered and deregistered cars. For every newly registered car due to the subsidy a car in the same segment, manufactured 2010 or earlier, is disposed. Vehicle purchases in higher segments are not subsidized.

"Innovation" Concept

With this concept, only BEVs are subsidized. For the baseline model, the same distribution of subsidized cars as in 3.6 is considered, except only BEVs will be newly registered due to the subsidy.

"Downsizing" Concept

Lastly, a concept is shown, which only allows a subsidy if the new car is at least one segment smaller (defined by the segment's CO_2 emissions) than the one traded-in. The respective segment shifts in the "downsizing" concept are displayed in Table 8.

Table 8. Segment shifts in "downsizing" concept

Segment of vehicle traded in	Segment of new vehicle
mini class	-
small class	mini class
compact class	small class
middle class	compact class
upper middle class	middle class
upper class	upper middle class
SUVs	middle class
mini vans	middle class
large vans	mini vans

As per CO_2 emission-based downsizing definition, the SUVs and mini vans are shifted to the middle class segment.

4. Results

The goal of this work is to analyze the subsidy impact on the CO_2 eq. emissions of the German passenger car fleet. This is achieved by considering categorized vehicle emissions and fleet composition data.

4.1. Life Cycle Analysis

The life cycle of a vehicle consists of production, maintenance, use phase, and EoL processes. For each element, the respective emissions are calculated per segment and per drive train technology.

4.1.1. Production

Using the described process in 3.5.1, an analysis of the production emissions for each vehicle is made.

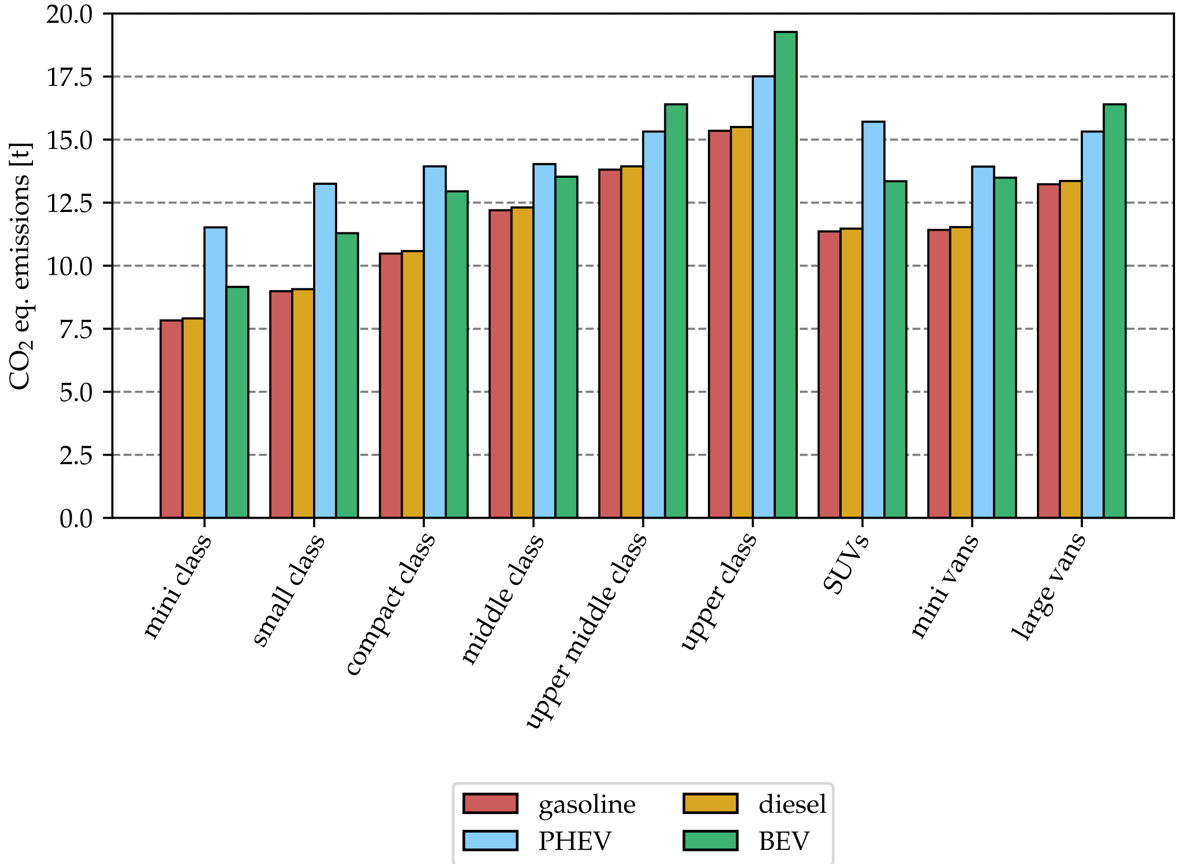

Figure 9. Production emissions

The production of BEVs and PHEVs results in higher CO_2 equivalent emissions than the production of conventional vehicles. This phenomenon emerges in every segment and can be attributed, in addition to the higher vehicle weight of BEVs and PHEVs, to the greater effort of producing batteries and electrical parts. The BEV production effort increases substantially for larger segments as more battery capacity is implemented. This effect is less pronounced for PHEVs.

4.1.2. Maintenance

The emissions from the vehicle and road maintenance per driven kilometer (Figure 10) scale mainly with the vehicle weight.

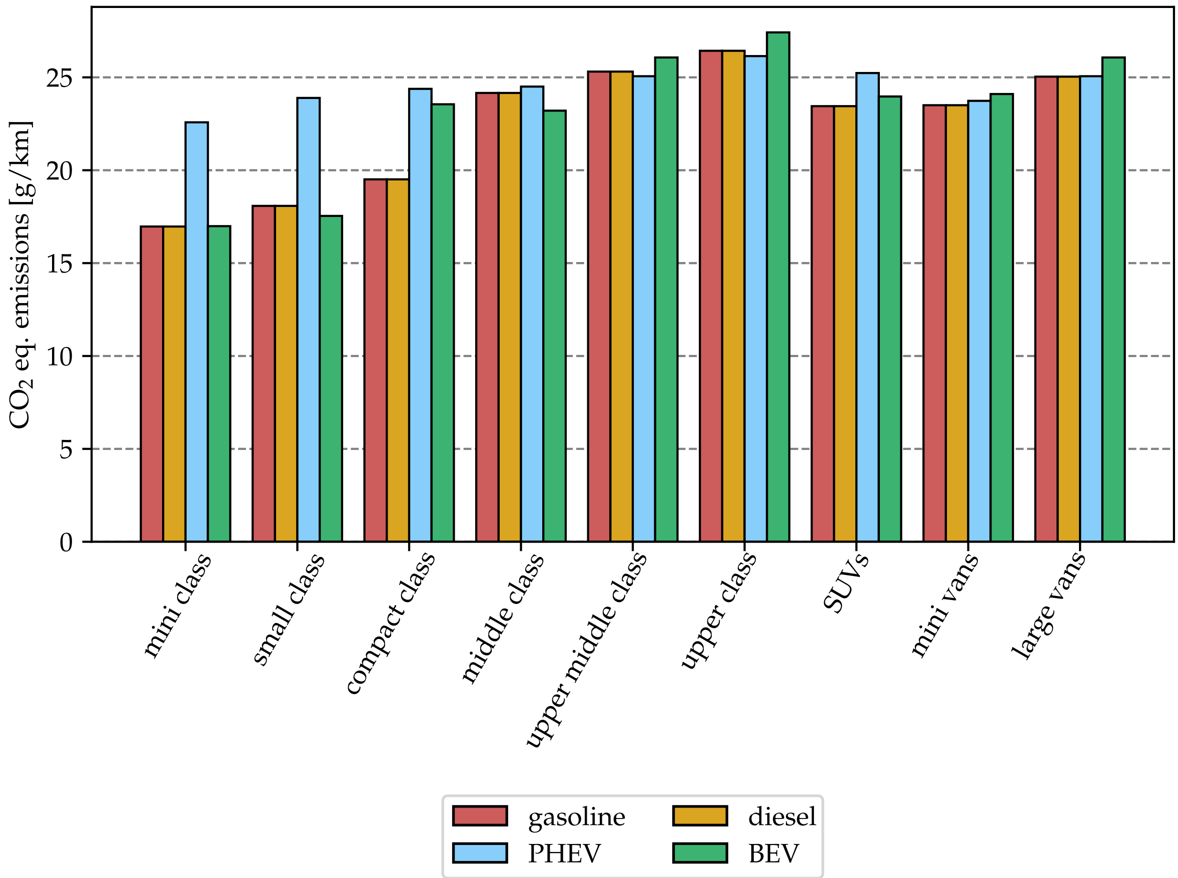

Figure 10. Maintenance emissions

4.1.3. Use Phase

The CO_2 equivalent emissions are depending on the vehicle specifications. In addition to the direct exhaust emissions, vehicles with combustion engines cause indirect emission via the procurement of the fuel. Figure 11 shows the combined specific CO_2 eq. emissions per kilometer in 2019.

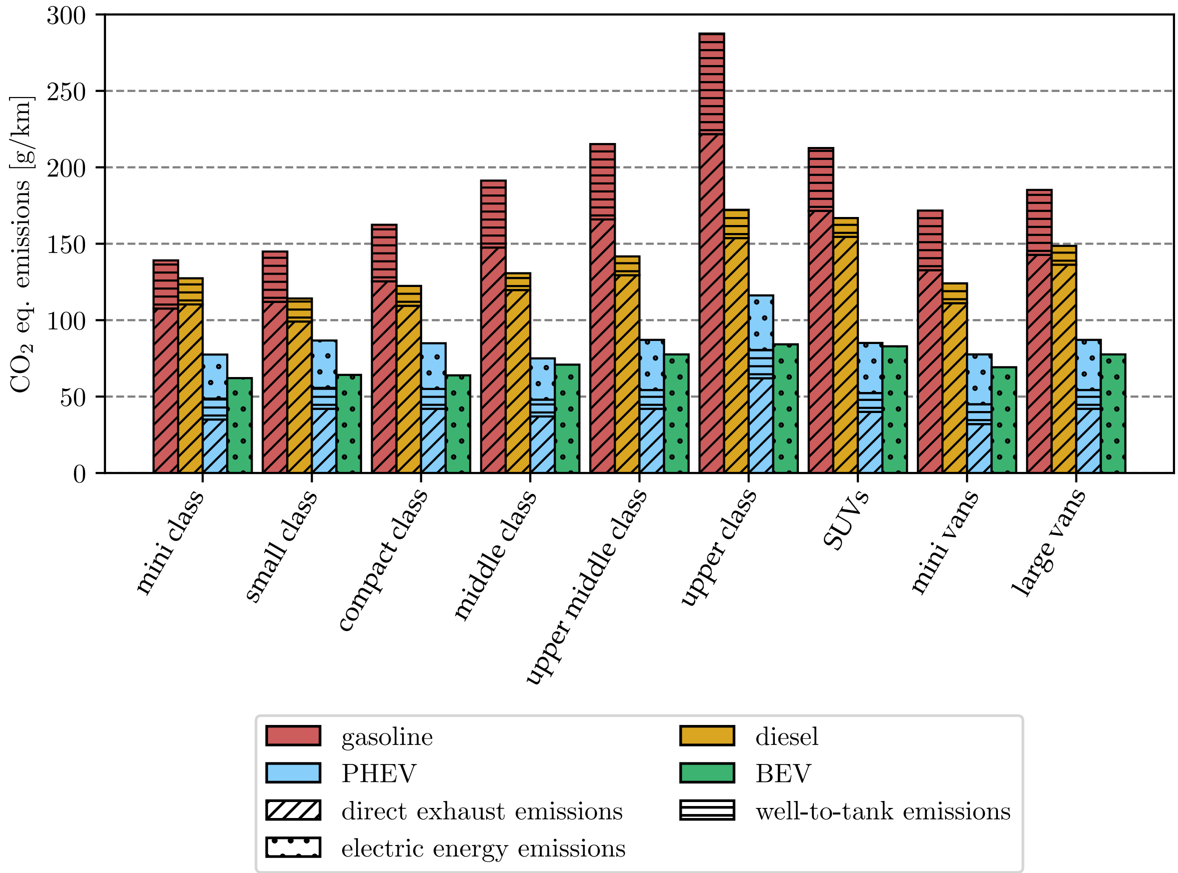

Figure 11. Composition of CO_2 eq. emissions per driven kilometer

Vehicles with a gasoline engine have the highest specific emissions across every segment followed by diesel engine vehicles. The BEVs have the lowest specific emissions of the considered drive train technologies throughout all segments.

4.1.4. End-of-Life

Due to the high recycling effort of the batteries, we see increased EoL emissions of the BEVs and PHEVs compared to the conventionally powered vehicles (Figure 12). The higher battery capacity in larger segments leads to higher EoL emissions of the BEVs compared to the PHEVs. Again, the vehicle weight is an important driver of EoL emissions.

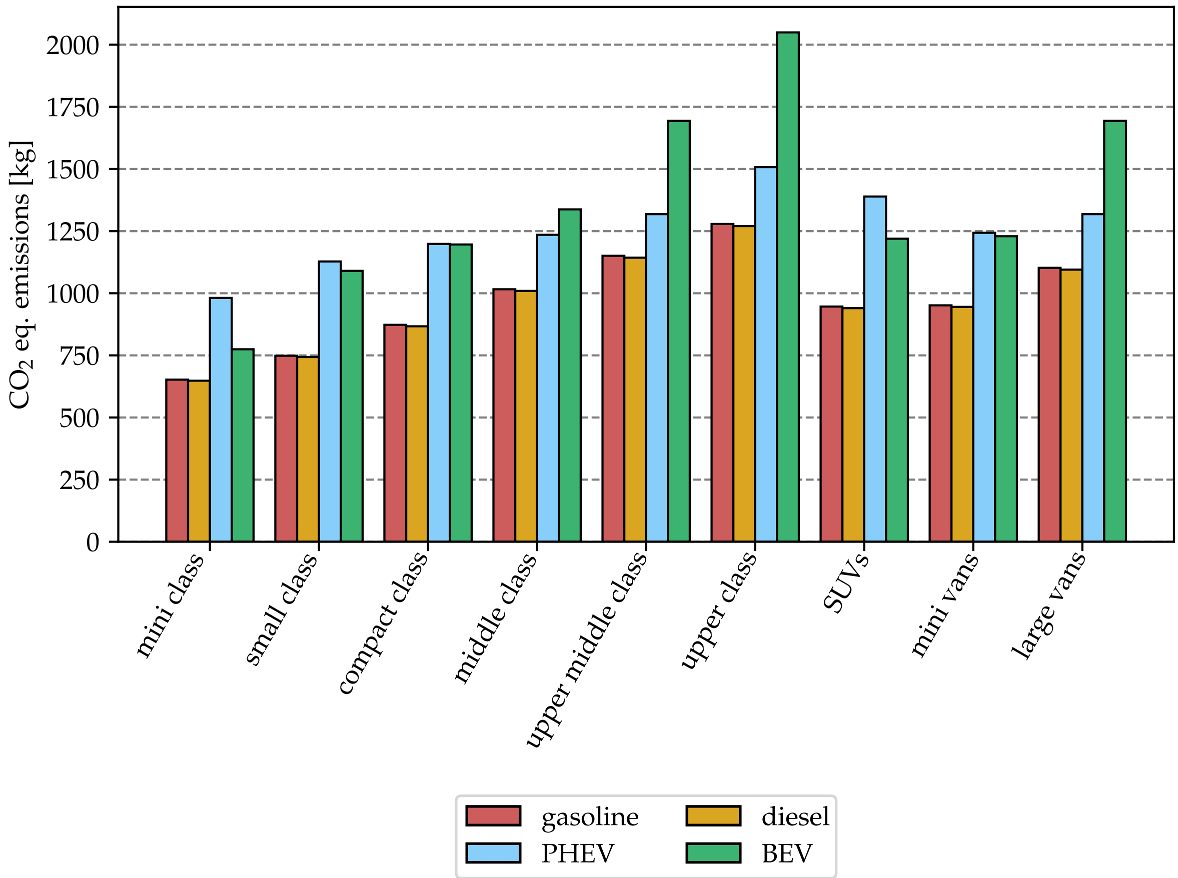

Figure 12. End-of-Life emissions

4.2. Subsidy Impact on Fleet Emissions from 2019-2030

Using a combination of the results from 4.1 and the German car population scenario from 3.3, a prediction of the emitted CO_2 equivalent emissions from the German passenger car system until 2030 is made. The emitted emissions decrease in 2020 due to reduced vehicle production (Figure 13). As shown in Figure 7, the vehicle production increases in the subsequent years due to the subsidy. Therefore, higher emissions are expected before the vehicle fleet benefits from the increased efficiency which leads to reduced annual emissions.

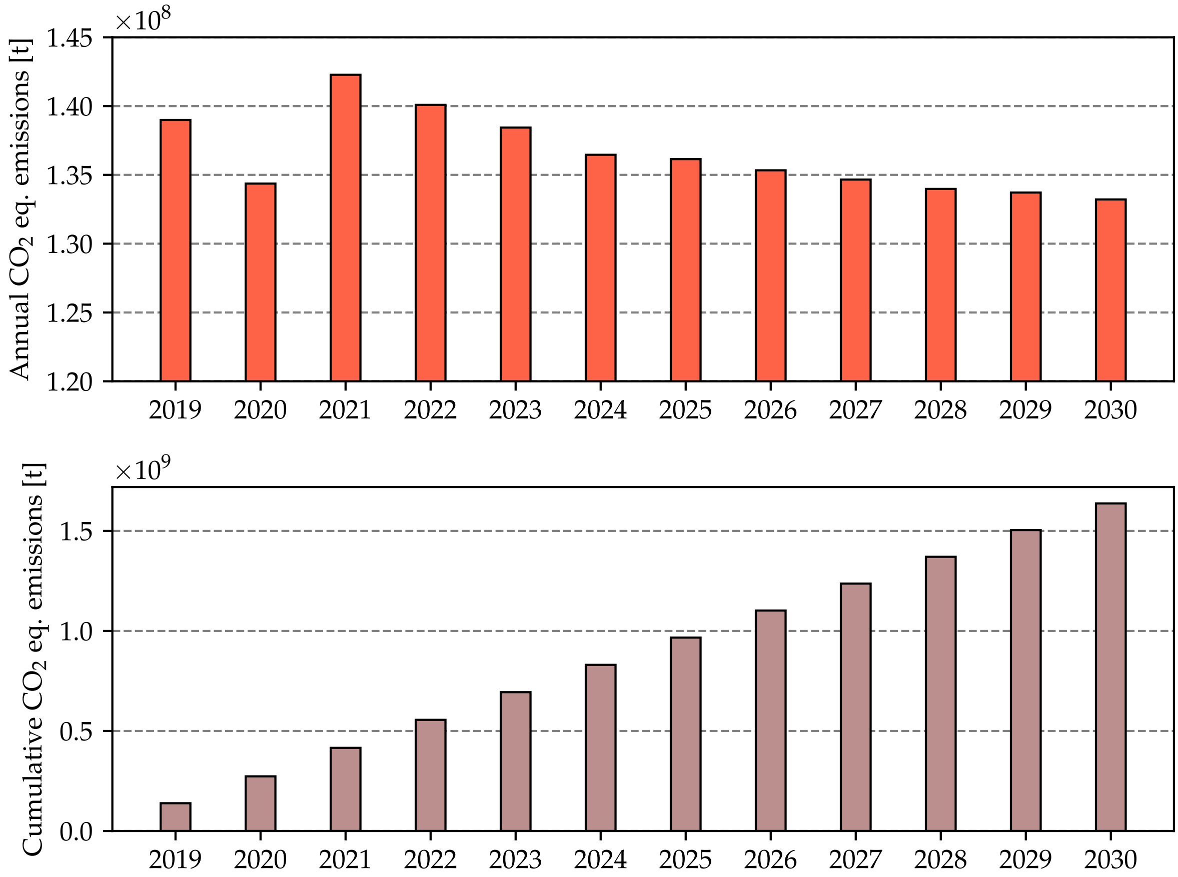

Figure 13. Life cycle CO_2 eq. emissions of the baseline scenario without a subsidy

The cumulative CO_2 eq. emissions of the baseline scenario without a subsidy (Figure 13) are compared to the cumulative emissions of the various subsidy concepts. Each concept is calculated with 0.72 million subsidized vehicles. The developed model enables the analysis of any number of subsidized vehicles.
Figure 14 shows the comparison of the different subsidy concepts relative to the baseline scenario. As a result, the accumulated differences of the CO_2 equivalent emissions are shown for the respective scenario.

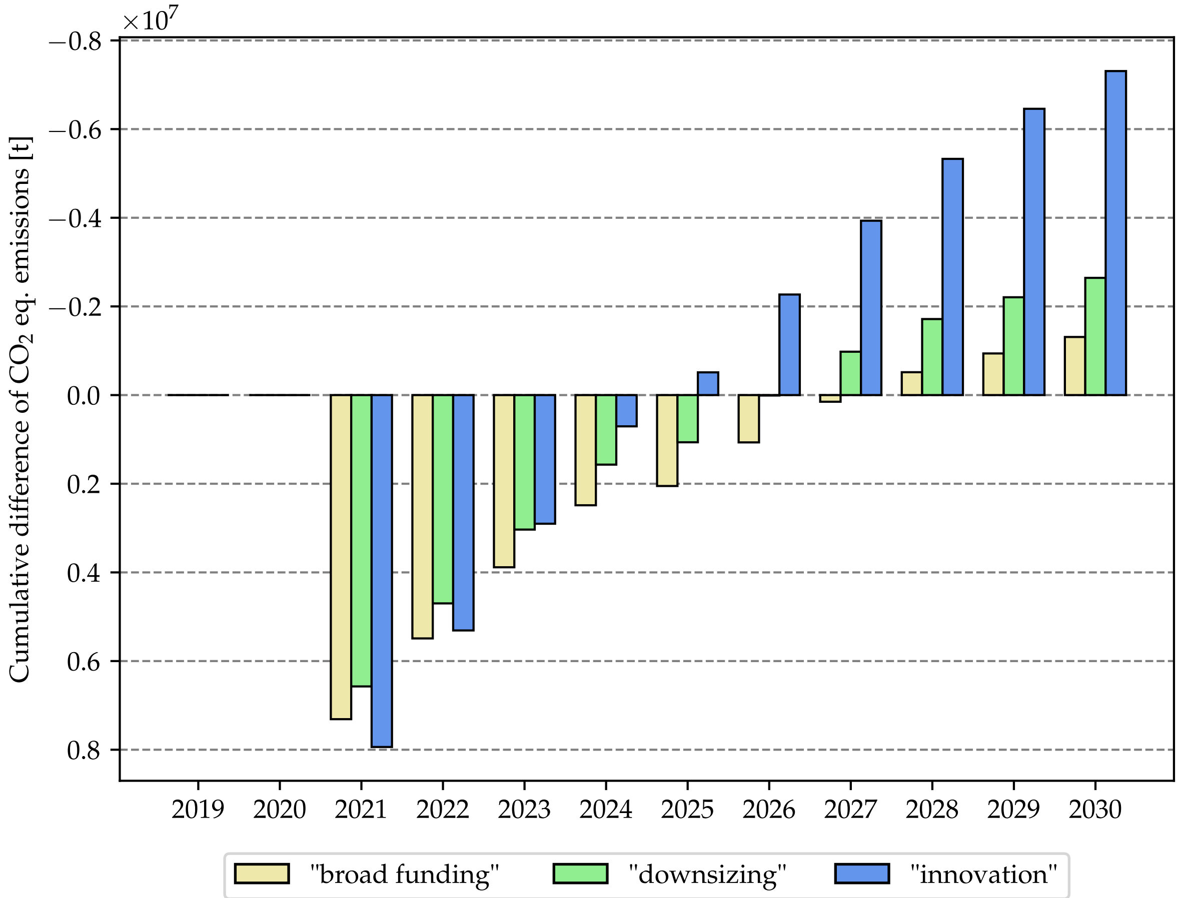

Figure 14. Cumulative difference of CO2 eq. emissions to no subsidy scenario

The cumulative difference shows significant additional emissions in 2021 for all subsidy concepts. The effect displays the higher number of new vehicles and the related production emissions for this year. The emission savings are dependent on the subsidy concept.

The "innovation" subsidy clearly lowers the CO_2 equivalent emissions of the German passenger car transport system until 2030 the most out of all considered concepts. Even with the highest CO_2 equivalent emissions in 2021, the "innovation" concept reaches the break-even earliest in the year 2025. The additional CO_2 equivalent emissions of the "innovation" concept in 2021 are 8.6% higher than the "broad funding" and 20.8% higher than the "downsizing" concept. This effect can be attributed to the higher production effort of electric vehicles as shown in Figure 9.

Regardless of the highest CO_2 equivalent emissions in 2021, the accumulated CO_2 equivalent emission savings until 2030 of the "innovation" concept are 285.7% higher than the "downsizing" and 576.7% higher than the "broad funding" concept. Compared with the scenario without a subsidy, the "innovation" concept reaches a cumulative difference of -7.56 $\cdot$ 10^6 t CO_2 equivalent emissions until 2030.

In the "downsizing" concept smaller vehicles, compared to the "broad funding" concept, are produced. Therefore, in 2021 the CO_2 equivalent emissions of the "downsizing" concept are lower than the emissions in the "broad funding" concept. In addition, the "downsizing" concept reaches the break-even point in 2027 one year earlier than the "broad funding" subsidy concept.

4.3. Sensitivities

Due to the complexity of the model, dependencies on key parameters are reviewed and their respective impact on the subsidy concepts is determined.

4.4. Number of subsidized cars

As shown in 3.4, we assume the number of subsidized cars match the predicted registration decrease in 2020 due to Covid-19 pandemic. To determine the impact of the number of subsidized cars (∼0.7 million), this value is doubled (∼1.4 million) and quadrupled (∼2.8 million).

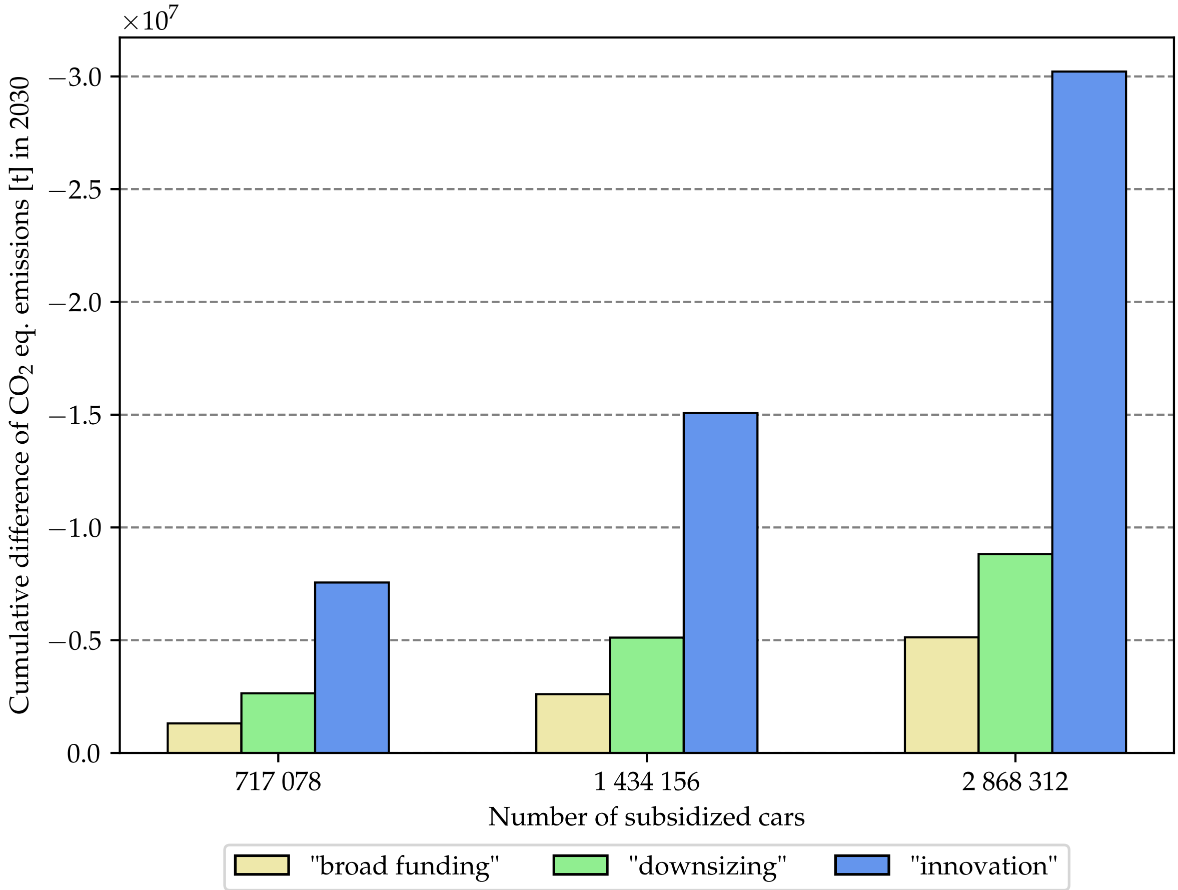

Figure 15. Number of subsidized cars

As expected the cumulative difference of CO_2 eq. emissions in 2030 is proportional to the number of subsidized cars.

4.4.1. Vehicle Distribution

As discussed in 3.6, the “environmental bonus” in 2009 was primarily used to purchase smaller vehicles. This can be attributed to the fairly high share of the subsidy compared to the purchase price. It would be conceivable to design the subsidy in a way that the amount is determined by a fixed percentage of the purchase price. It is assumed that this leads to a vehicle distribution of the subsidized cars proportional to the predicted new passenger car registrations in 2021.

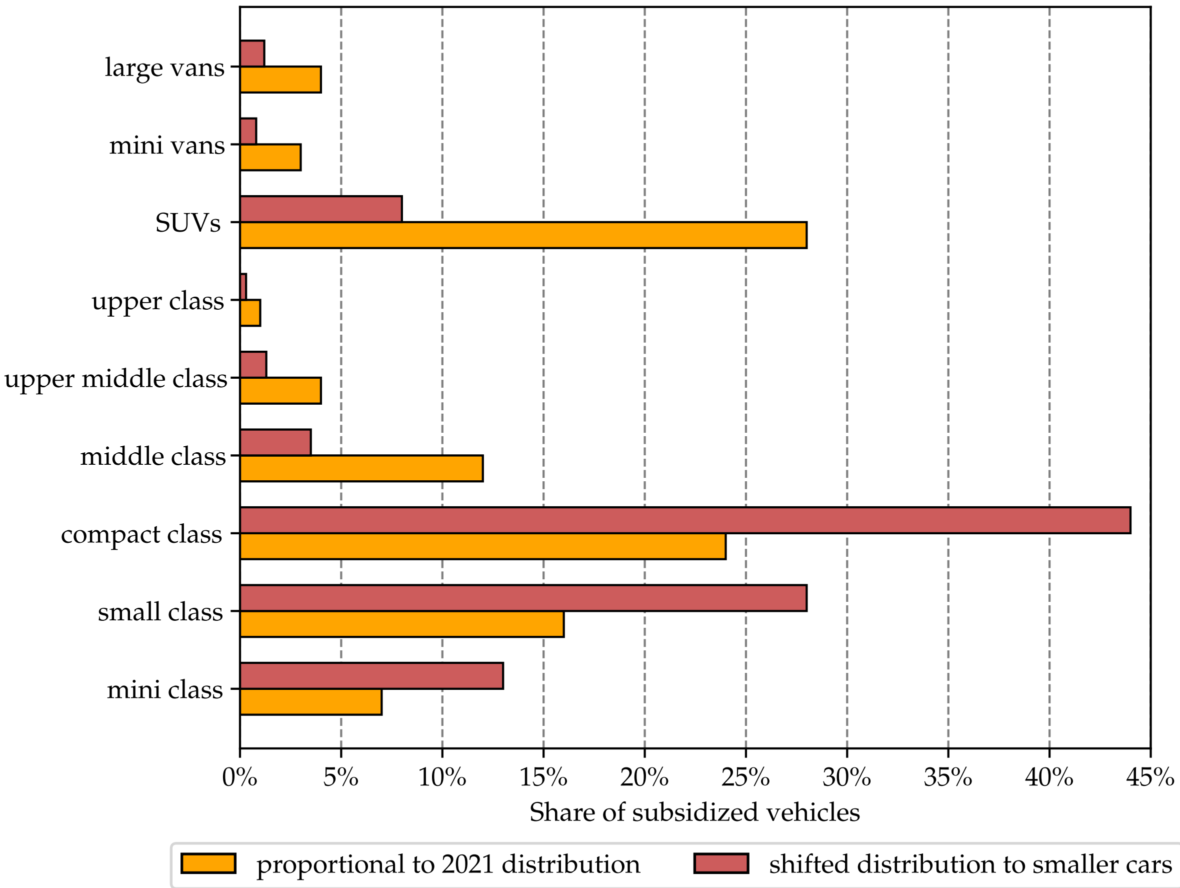

Figure 16. Subsidized car distribution for two scenarios under investigation

Figure 16 shows the difference between a scenario proportional to 2021 and a scenario shifted to smaller cars. The modified distribution of subsidized vehicles has an impact on the results.

Table 9. Difference of cumulative CO_2 eq. emissions to no subsidy scenario in 2030

Subsidy concept	Difference to "without subsidy" baseline	
	Shifted distribution to smaller cars	Proportional to 2021 distribution
"broad funding"	-0.080%	0.037%
"downsizing"	-0.161%	-0.017%
"innovation"	-0.462%	-0.401%

As shown in Table 9, all subsidy concepts are less efficient using the distribution proportional to 2021. In this context, the "broad funding" concept even increases the CO_2 eq. emissions compared to the no subsidy baseline. As a result, subsidizing smaller cars are increasing the efficiency of the subsidy significantly.

4.4.2. New Vehicles Registrations

Drive Train Technologies

To predict the German car population until 2030, we rely on 3.3 on the "ProKlima" scenario stated in Agora 2018 [20] to describe the trend of the drive train technologies. To estimate the impact of the subsidy for a baseline scenario with a higher share of newly registered PHEVs and BEVs, an analysis with the “ProKlima Plus” scenario is made.

Table 10. Share of annual newly registered cars

Drive train technology	“proKlima” 2025	2030	“proKlima plus” 2025	2030
gasoline	57%	42%	27%	28%
diesel	29%	19%	28%	10%
PHEV	8%	22%	20%	29%
BEV	6%	18%	25%	47%

In Table 10 the values for the drive train technology development of the different scenarios can be seen. To determine the share of newly registered cars for each year, a linear interpolation between the displayed values is made.

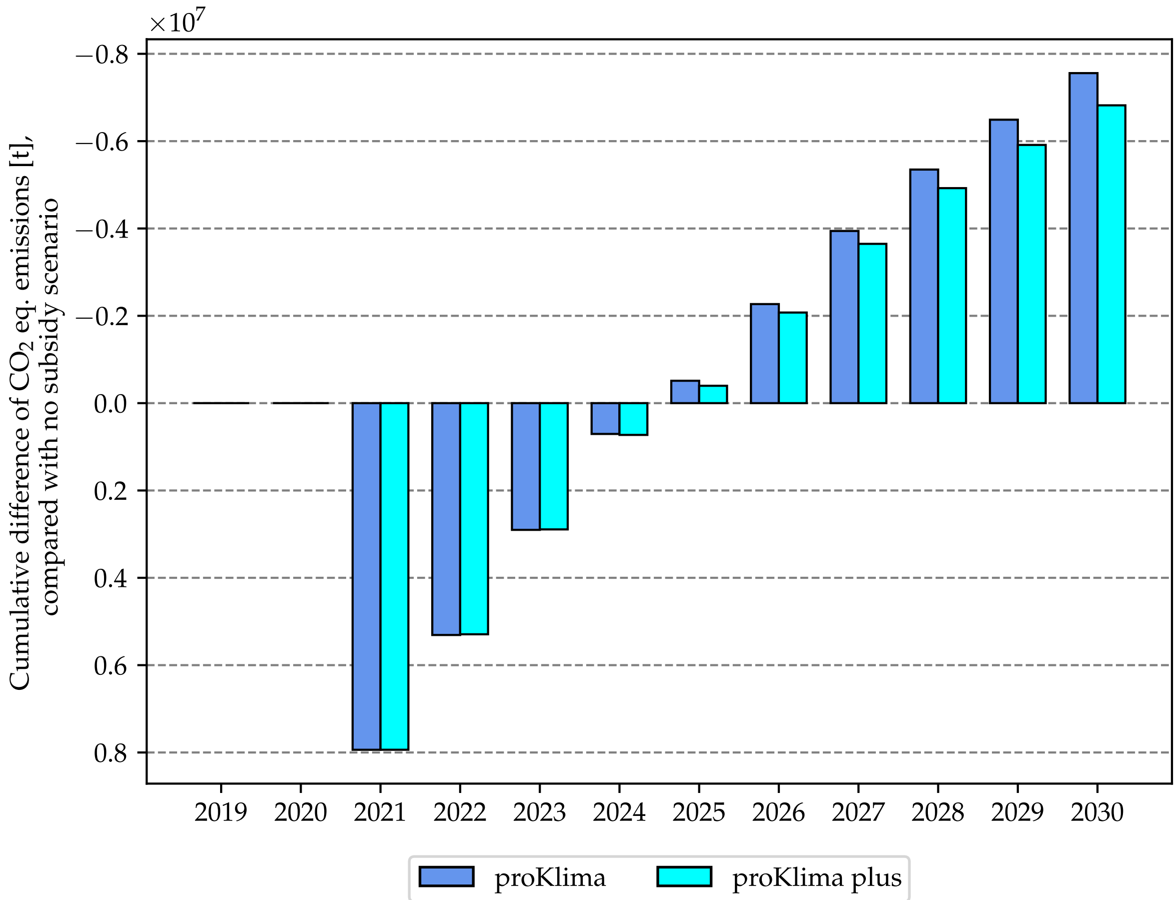

Figure 17. Cumulative CO_2 eq. emissions difference between “no subsidy” baseline and “innovation” concept using the “proKlima” and “proKlima plus” registration predictions

Figure 17 shows the cumulative CO_2 eq. emissions difference of the “innovation” concept with the two different assumptions for the annual newly registered cars until 2030. It is shown that the subsidy loses efficiency if the baseline share of PHEVs and BEVs rises. The cumulative CO_2 eq. emissions difference will be smaller due to the overall more efficient German passenger car fleet with the “proKlima Plus” scenario.

Segments

In 3.3 an assumption of the development for the segment composition of newly registered cars is introduced. Here, we assume that the SUVs segment will reach a 40% share of the annual newly registered cars in 2030. Since this parameter is uncertain, analysis with either 30% or 50% SUVs of the newly registered cars in 2030 is made. Investigating the "innovation" concept, the 30% SUV share scenario is generating 2.40% less CO_2 eq. emissions savings compared to the 40% SUV share baseline due to the overall more efficient car fleet. Contrary, the cumulative CO_2 eq. emissions savings of the "innovation" concept in the 50% SUV share scenario are 0.84% higher compared to the baseline.

This shows that the results of the study are robust against this parameter because the trend and the statement of the results are not changed by a variation of the SUV share.

5. Discussion

The absolute CO_2 eq. emissions savings are proportional to the number of subsidized cars. For the results shown, we set the subsidized cars in the model to about 0.72 million cars. This is more conservative than the actual replacements of 1.95 million [3] during the 2009 "environmental bonus". In case the 2020 program would have the same impact on car sales, the absolute savings grow accordingly.
In absence of detailed prognosis data for the technological improvements, we assume no efficiency gains regarding the CO_2 eq. emissions. The trend of the combustion engines indicates a saturation for the CO_2 efficiency [44]. Assuming that the electric drive train technologies will still gain efficiency [52] and more electricity will be generated from renewable sources, the total savings for the "innovation" concept would be higher.
Since only the direct CO_2 emissions for the driving during the use phase of combustion engines are available, the actual CO_2 eq. emissions are slightly higher. As this effect is not relevant to BEVs since CO_2 eq. emissions are considered for the electricity production, the "innovation" concept would generate marginally higher savings when considering all emissions from the combustion engines.

This paper shows that all considered subsidy concepts have eventually a positive effect on reducing the CO_2 equivalent emissions of the German passenger car fleet. This corresponds with both, Höpfner et al. [3] and Lenski et al. [13], which stated that the 2009 car subsidy had a positive effect on the environmental performance of the various car fleets.
Contrary to Klößner et al. [8], the long term effect on the CO_2 emissions is positive as windfall gains (subsidized purchases that would happen without the subsidy) are not included and BEVs and PHEVs are considered. We only expect additional CO_2 emissions to occur immediately after the subsidy is introduced due to the increased production which is overcompensated by savings during the use phase.

To calculate the LCA emissions we clustered the vehicle fleet into segments to reflect the actual distribution. Agora 2019 [53] used only one reference vehicle for each drive train technology. For a comparable segment, the production emissions of the BEVs show similar results. In this work, the gasoline and diesel vehicles result in higher production emissions compared to Agora 2019 [53]. This can be attributed to a deviation in parameter settings.

6. Conclusion

In order to calculate the cumulative CO_2 eq. emissions of the German passenger car fleet from 2019-2030 a granular model is developed. Three different subsidy concepts are introduced and the impact on the CO_2 eq. emissions is determined.

Subsidizing the German passenger car system due to the Covid-19 pandemic shows long term CO_2 emissions savings for nearly all investigated scenarios. Only in the sensitivity analysis

the “broad funding” concept leads to slightly increased emissions when using a vehicle distribution proportional to 2021. Taking the sensitivity analyses into account, the “innovation” concept shows the most significant emission savings on the German passenger car system.
Considering the time period 2019-2030 and a total number of 0.72 million subsidized vehicles, the “innovation” concept generates about 7.56 million t less CO_2 eq. emissions compared to the scenario without a subsidy. This equates to 0.46% of the total CO_2 eq. emissions of the addressed segments in this period. The “downsizing” and “broad funding” concepts create saving of 0.16% and 0.08%, respectively.

In 2021 the increased vehicle production leads to higher CO_2 emissions for all subsidy scenarios compared to the scenario without a subsidy. The ecological break-even is reached in 2025 for the “innovation” concept, in 2027 for the “downsizing” concept, and in 2028 for the “broad funding” concept.

If from an economic and political point of view a subsidy program for passenger cars in Germany is considered to be desirable, we clearly recommend the exclusive funding of BEVs because the “innovation” concept achieves the highest positive climate impact at the earliest time.

7. Outlook

To further investigate the environmental impact of passenger car subsides in Germany additional greenhouse gases in the use phase and air pollutants must be considered. It seems reasonable to add greenhouse gases with a high GWP. Due to the current discussion on driving bans in German city centers, the subsidy impact on nitrogen oxides would enhance the model result.

It is conceivable to examine further subsidy concepts such as focusing on PHEVs or particular segments.
In the current model, the technological status of the vehicles is assumed to remain at the level of 2019. Only the indirect emissions of BEVs and PHEVs will decrease until 2030 due to the slight reduction of the specific carbon dioxide emissions of the German electricity mix. This means the vehicle weight and direct exhaust emissions of each newly registered vehicle will remain constant in the current model.
In our model, we define a reference vehicle to describe the BEVs and PHEVs due to lacking data provided by the KBA. To obtain the detailed PHEVs and BEVs model parameters more precisely, data of all vehicles available needs to be consolidated.
As Höpfner et al. [3] notes, the vehicle subsidy in 2009 led to reduced used car sales. This is not implemented in the current model and might affect the disposal rate and the number of newly registered cars.

This paper does not investigate the economic impact of subsidy scenarios. A detailed market analysis is needed to estimate consumers buying behavior. To improve the model, it is necessary to further examine the subsidy’s impact on the newly registered cars and address economic effects like on-top sales and windfall gains.

Supplementary Materials: The following are available online at http://www.mdpi.com//1/1/0/s1 , Table S1: Direct CO_2 emissions per kilometer, Table S2: Fuel consumption per 100 kilometer

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