Paul Scherrer Institut

Vehicle retire-and-replace subsidy programs – The Life Cycle Perspective

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https://www.psi.ch/en/ta

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1 Summary

Vehicle scrappage programs from a life-cycle perspective

Environmental assessments of vehicle scrappage programs are often limited to evaluating the reduction of direct air pollutant emissions due to replacement of old vehicles with new ones exhibiting lower tailpipe emissions and higher fuel efficiencies. However, non-direct emissions (i.e. those associated with fuel supply, vehicle production and disposal) contribute considerably to the overall environmental impact of vehicles over their lifetimes, especially in the case of battery electric vehicles (BEV). Accounting for these indirect emissions of air pollutants, as well as greenhouse gases (GHGs), is essential to design programs providing benefits to local air quality and climate change mitigation from a more comprehensive perspective.

Several generic studies determined the optimal lifetime of internal combustion engine vehicles minimizing certain life-cycle air pollutant (NO_x, CO and VOC) and GHG emissions. A common finding is that a more frequent replacement of vehicles minimizes air pollutant emissions, while a long vehicle lifetime reduces GHG emissions, as fuel economy improvement rates do not outbalance emissions from vehicle production and disposal.

A limited number of studies evaluated the life-cycle performance of specific scrappage programs. These studies found that introducing a scrappage program yields a moderate reduction or neutral effect on GHG emissions. A specific evaluation of the US Consumer Assistance to Recycle and Save act (CARS) introduced in 2009 concluded that emissions of VOC, NO_x and GHG decreased. Conversely, particulate matter (PM) and SO_x emissions increased as production and disposal emissions of these pollutants are substantial.

Our present evaluation of the German “Abwrackprämie” in 2009 similarly concludes that local air pollutant emissions were reduced, while life-cycle effects were more ambiguous. Life-cycle NO_x emissions were reduced, while PM and SO_2 emissions increased. The effect on GHG emissions was uncertain and depended largely on the assumptions regarding annual kilometers driven, the lifetime reduction of the replaced vehicle, vehicle lifetime as such and fuel economy improvement. While past assessments of specific scrappage programs found fuel economy improvements of 20-25%, we estimate that the German program improved fuel economy by only about 10%. As a consequence, the program caused a neutral effect or a slight increase in GHG emissions.

Additionally, we evaluate a hypothetical program of similar scale, replacing diesel vehicles with BEV in German cities exceeding the NO_2 concentration limit. While local air quality would profit from such a retire-and-replace program, indirect emissions would increase. The reduction in direct NO_x emissions would be large enough to offset the increase in indirect emissions, while overall PM and SO_2 emissions would increase. The effect on GHG emissions depends on the electricity supply considered for BEV charging: only if the additional electricity demand were covered by low-carbon power generation, prematurely retiring diesel vehicles and replacing those with BEV would reduce overall GHG emissions. This shows that retire-and-replace programs limited to BEV have larger potential for NO_x emission reductions than past programs, but to avoid an increase in GHG emissions, the additional electricity demand must be met by an electricity mix with substantially less coal power than the current German one.

Figure 1 summarizes the effects of various specific scrappage or replace-and-retire programs, in the past and today, from a life-cycle perspective.

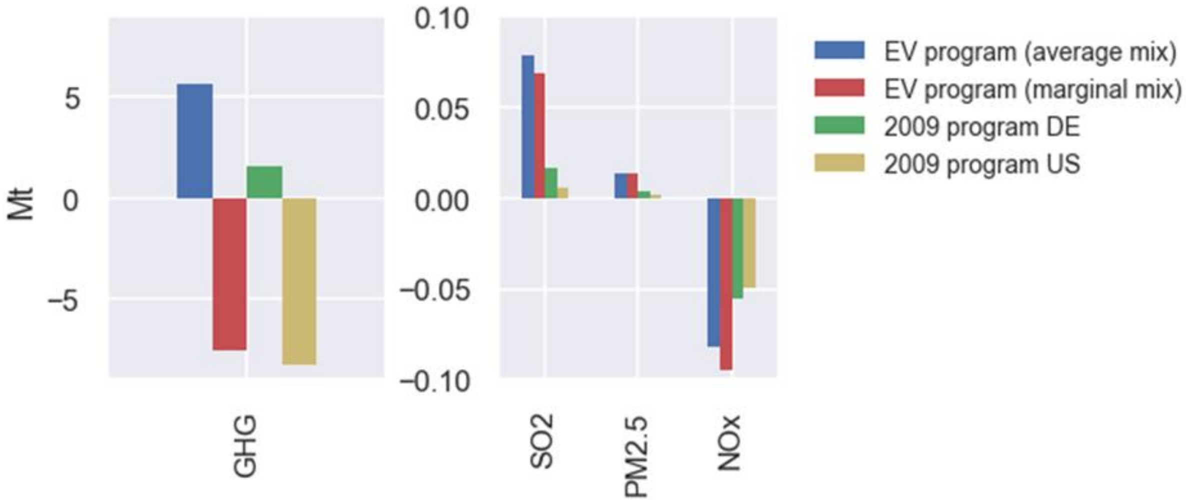

Figure 1 Effect on life-cycle emissions from introduction of different scrappage programs. EV programs refer to the hypothetical German program replacing about 2 million diesel vehicles with electric vehicles today. The 2009 program in Germany (DE) refers to our analysis of the "Abwrackprämie", while the "2009 program US" shows the results from the assessment of CARS by [1]. "Average" and "marginal" mix refers to electricity supply for charging BEV: The average mix represents current German electricity supply, while the (long-term) marginal mix corresponds to the coverage of additional electricity demand taking into account the phase-out of coal power and the expected expansion of renewables in Germany.

2 Introduction

Air pollution causes significant damage to human health and economic impacts by life lost, labour and medical costs in Europe [2]. Road transport is a main contributor to this and many of the urban areas with the highest number of transport-attributed premature deaths are located in Europe [3]. Scrappage programs are considered as one of the tools to improve air quality and aim at replacing high-emitting old vehicles with new, more efficient ones by offering a subsidy to vehicle owners. Such programs are beneficial to reduce direct emissions of air pollutants, but will also stimulate the car manufacturer industry [1,2] and accelerate adaption of new technologies. A study from the US [6] found that vehicle fleet renewal rates are slow and if every new vehicle sold were electric from today on, it would take until 2040 before they constitute 90% of in-use vehicles. Hence, accelerating the transition of the vehicle fleet may be needed to realise goals set for electric mobility in various countries.

Past environmental assessments of scrappage programs are often limited to evaluating the reduction in direct air pollutant emissions [4], [7]–[9]. However, non-direct emissions[1] contribute considerably to the overall environmental impact of vehicles, especially in the case of new vehicle technologies such as battery electric vehicles (BEV). Accounting for these indirect emissions of air pollutants as well as greenhouse gases (GHGs) is essential to design programs providing benefits to local air quality and climate change mitigation.

This analysis focuses on the case of Germany, where a large scrappage program was implemented during the economic crisis in 2009. First, this program is analyzed from a life-cycle perspective and important factors are identified. Second, a hypothetical current program is assessed aimed at replacing diesel cars with BEVs in German cities where NO_2 concentration limits are exceeded. Regional differences in human health impacts are also considered. Finally, a potential future program (2030) is assessed.

With our analysis, we want to answer the question, whether prematurely scrapping old vehicles and replacing them with new ones is beneficial from the environmental perspective, not only taking into account direct, but also indirect emissions related to the production (and disposal) of vehicles.

This report is structured as follows: section two presents relevant literature assessing scrappage programs from a life-cycle perspective, section three describes the calculation methodology and data sources, section four presents and discusses the results, while section five concludes.

3 Literature review

Two separate bodies of literature are identified addressing environmental impacts of scrappage programs from a holistic perspective. First, several studies determine the optimal vehicle lifetime minimizing certain life-cycle air pollutant (NO_x, CO and VOC) and GHG emissions [7], [10]–[13]. A common finding is that a more frequent replacement minimizes air pollutant emissions, while a long vehicle lifetime reduces GHG emissions, as fuel economy improvement rates do not outbalance emissions associated with vehicle production and disposal.

Second, some studies evaluate the life-cycle effect of specific scrappage programs or vehicle replacement decisions [1], [14]–[16]. The evaluation of the “Cash for Clunkers” program in the US [1] demonstrated reduction in NO_x and VOC emissions, while PM emissions increased. Contrary to the studies stating that reducing vehicle lifetime increases CO_2 emissions, a moderate reduction in GHG emissions was found.

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[1] Emissions associated with fuel supply, production and disposal of vehicles

3.1 Vehicle lifetime and effect on GHG and air pollutant emissions

Introducing a scrappage program will shorten vehicle lifetime of old, fuel-inefficient cars as they are replaced with newer fuel-efficient vehicles with reduced emissions of air pollutants. However, a shortening of lifetime increases emissions associated with production and disposal. To be environmentally sound, the emissions "saved" must outbalance the emissions from production and disposal.

Spielmann and Althaus (2007) assessed the effects on CO_2, NO_x and $PM_{2,5}$ emissions of a prolonged car use in Switzerland. They concluded that extending vehicle lifetime from 12 to 15 years lowers environmental burdens, as the increase in emissions of a prolonged use of a less fuel-efficient car is outbalanced by savings in car production and disposal. Similarly, Kagawa et al. (2011) and Van Wee, Moll and Dirks (2000) conclude that shortening vehicle lifetime of petrol cars increases CO_2 emissions, while emissions of NO_x, HC and CO moderately decrease. The benefit of a longer lifetime on CO_2 emissions decreases if the annual fuel economy improvement rate increases. A study of the Dutch car fleet found that the yearly improvements in fuel economy would need to increase to bring reductions in CO_2 emissions from a shortening of lifetime [11]. Also in Switzerland past improvements in fuel efficiency in the period from 2000 to 2010 were not sufficient to compensate for emissions from other life-cycle phases [10].

Spitzley, Grande, Keoleian and Kim (2005) consider optimal vehicle replacement intervals under a period of 36 years in the US. They conclude that shorter replacement intervals (3 to 6 years), minimizes emissions of CO, NO_x and NMHC. On the other hand, longer replacement intervals of 18 years yield the lowest total life-cycle CO_2 emissions. Likewise Kim, Ross and Keoleian (2004) find that scrapping vehicles younger than 20 years and produce new slightly increases CO_2 emissions. Finally, a country specific study finds that extending vehicle lifetime in countries like Japan or Germany, where current average vehicle lifetime is shorter than the global average, can be effective in reducing CO_2 emissions [13].

3.2 Scrappage programs from a life-cycle perspective

Lenski et al. (2010) evaluated the US Consumer Assistance to Recycle and Save act (CARS) of 2009. Including production and disposal emissions reduces emission savings by 18%. A net saving of 4.4 mio metric tons CO_2-equivalents (0.4% of annual light duty vehicle emissions) was identified, but results are sensitive to remaining lifetime. Later, the analysis was extended to include life cycle emissions of VOCs, NO_x, $PM_{2,5}$, PM_{10} and SO_x. Emissions of VOCs and NO_x decrease as a result of CARS, while $PM_{2,5}$, PM_{10} and SO_x emissions increase as production and disposal emit a significant amount of these pollutants [1].

Lelli, Pede, Valentini and Masoni (2010) present life-cycle GHG emissions of a hypothetical car scrappage scheme running for 24 years based on characteristics of the Italian car fleet and generic life cycle results. The study concludes that the scheme has a neutral effect on GHG emissions if limited towards purchase of more fuel-efficient vehicles.

Kagawa et al. (2013) evaluate a Japanese scrappage scheme considering full life-cycle emissions using environmental extended input-output methods. Overall, the scheme contributes to a moderate reduction of about 1 million ton CO_2 emissions when accounting for manufacturing and disposal. Kagawa et al. (2011) also find that increasing the market share of hybrid vehicles can reduce the increase in CO_2 emissions. The (remarkable) increase in the hybrid market share in Japan between 2000 and 2009 implies that a vehicle lifetime reduction of 2.1 years still can have a neutral effect on life-cycle CO_2 emissions.

Messagie, M and Boureima, F and Sergeant, N and Timmermans, JM and Macharis, C and Van Mierlo (2012) evaluate the environmental performance of scrappage decisions in the Belgian context. For climate change the modelled BEV had the lowest impact and replacing conventional vehicles with a

BEV would reduce impacts even when accounting for the additional manufacturing required. Replacing conventional vehicles with a hybrid vehicles is also found to have positive impact on GHG emissions.

3.3 Factors influencing the environmental performance of scrappage programs

Previous studies have underlined the uncertainty linked to emission reductions attributable to scrappage programs, as the environmental performance is influenced by both behavioral and economic factors. Key parameters include annual kilometers driven by scrapped and replacement vehicles, actual reduction of pollutant emissions due to new regulations, fuel economy improvement and vehicle lifetime reduction [18]–[21]. Additionally, an important downsizing effect (i.e. people purchase smaller vehicles under scrappage programs) is identified from past programs [22]–[24].

3.3.1 Annual kilometers driven

The annual kilometers driven by cars are influenced by vehicle age, size and powertrain, as well as income and household structure ([9], [25], [8], [14]). Annual vehicle kilometers traveled is in general decreasing with vehicle age ([9], [17], [25], [26]), which may indicate that the replacement vehicle is driven more than the clunker.

The rebound effect is one reason for the potentially increased kilometers driven by a new vehicle. New vehicles are more fuel efficient, which reduces the marginal cost of driving. However, scrappage programs have in several cases lead to downsizing of the vehicles [22], [23]. West et al. (2017) find no evidence for an increase in kilometers driven under CARS in the US. The fuel economy restrictions lead households to purchase more fuel-efficient, but also smaller and lower-performing cars. While the first could increase the annual kilometers driven, the latter effect likely decreases it, leading to a net zero rebound effect. Several others also highlight the importance of vehicle attributes when considering the rebound effect, and highlight that shrinking size reduces the rebound effect [27]–[29].

3.3.2 Years remaining before natural retirement

The absolute emission savings from a scrappage program is sensitive to the number of years the vehicles are retired earlier. In the study by Lenski, Keoleian and Bolon (2010) of the US CARS program, emission savings close to double if the lifetime reduction doubles. The studies assessing the CARS program in the US estimate that vehicles are traded in 2.5-4 years earlier ([17], [19], [30]). To estimate the absolute emission savings the years remaining should be treated stochastically [15] and consumer choices and external factors will in addition to technical lifetime influence the lifetime reduction.

3.4 Studies of the German program in 2009

Only a few previous studies evaluate the environmental effects of the German scheme from 2009, but none of them consider life-cycle emissions. The most comprehensive study is done by Höpfner, Hanusch and Lambrecht (2009) and includes an evaluation of changes in direct air pollutant emissions and the improvement in fuel efficiency and CO_2 intensities. They find that the program was effective in reducing criteria pollutants and estimate NOx and PM tailpipe emission reductions of 87% and 99%, respectively. Despite mentioning the importance of upstream emissions from production and disposal, the study lacks a full life-cycle perspective.

Klöbner and Pfeifer (2015) find that the program reduced direct CO_2 emissions when introduced in 2009, while emissions in the following years increased. A temporal reduction in direct CO_2 emissions is also found in an analysis by Fraga (2011). The same study finds a reduction potential for NO_x and PM tailpipe emissions of 90 and 75%, respectively. Comparing the German scheme to the ones in the US and France, they conclude that the German scheme delivered lower environmental benefits at a higher cost. Compared to CARS in the US, the lower number of very old, high-emitting vehicles and the fact that real-world emissions of these were already lower in Europe reduced the effect on NO_x emissions. Similarly, the oldest vehicles in Germany were more fuel-efficient than the ones in the US, which lead to lower reductions in CO_2 emissions.

To summarize, a limited number of studies evaluate the life-cycle effect of scrappage programs. Many of these are limited towards one or a few air pollutants and CO_2 emissions [9], and particulate matter is only assessed by Lenski, Keoleian and Moore (2013). The majority of studies are limited to conventional vehicle scrappage programs, and evaluating the effect of scrappage programs involving BEVs or hybrid vehicles may change past conclusions [5], [9], [10].

In Germany several scrappage schemes have been introduced. In 2009 the large governmental scheme was implemented and today several car manufacturers offer scrappage incentives. By taking Germany as an example, this analysis uses a consistent, comprehensive set of life-cycle inventories for different powertrains, size and euro classes to address:

- Life-cycle environmental impacts of scrappage programs directed towards electric vehicles and the trade-off between local air quality benefits and potentially increased indirect emissions
- At which point in time can a German scrappage program be most effective - 10 years ago, today or 10 years in future?

4 Method

4.1 Calculation framework

To calculate the life-cycle effect of the scrappage programs a framework similar to the one established by Lenski, Keoleian and Bolon (2010) is used. Two different scenarios are defined. In the “business as usual scenario” (BAU) the old car is driven until the end of its natural lifetime and then replaced by a second, new car. In the “scrappage program scenario” (“retire-and-replace”, RaR) the old car is disposed of earlier and its “natural” lifetime reduced. Therefore, a second, new car is purchased at an earlier point in time. The timeframe considered is the usage of the two vehicles in the RaR scenario. The second vehicles purchased in both scenarios are assumed to have the same characteristics, emission standard and fuel economy. The lifetime of the second vehicle is assumed to be 200’000 km.

The reduced impact due to the program will be caused by reduction in direct and fuel chain related emissions between point x_2 and x_1 in time, which is the years between natural and earlier disposal of the first vehicle (due to the fact, that the new vehicle consumes less fuel and emits less air pollutants). In addition, the production and disposal emissions within the timeframe are higher when introducing a scrappage program as the vehicle lifetime of the first vehicle is shortened: While the entire production and disposal related emissions of the second vehicle are within the timeframe considered in the RaR scenario, a certain fraction of these are not within the timeframe in the BAU scenario, i.e. these are not accounted for. Hence, the difference in production and disposal emissions between the BAU and RaR scenarios increases the life-cycle impacts of the RaR scenario. By considering these two effects, the overall life-cycle impact of the program is quantified.

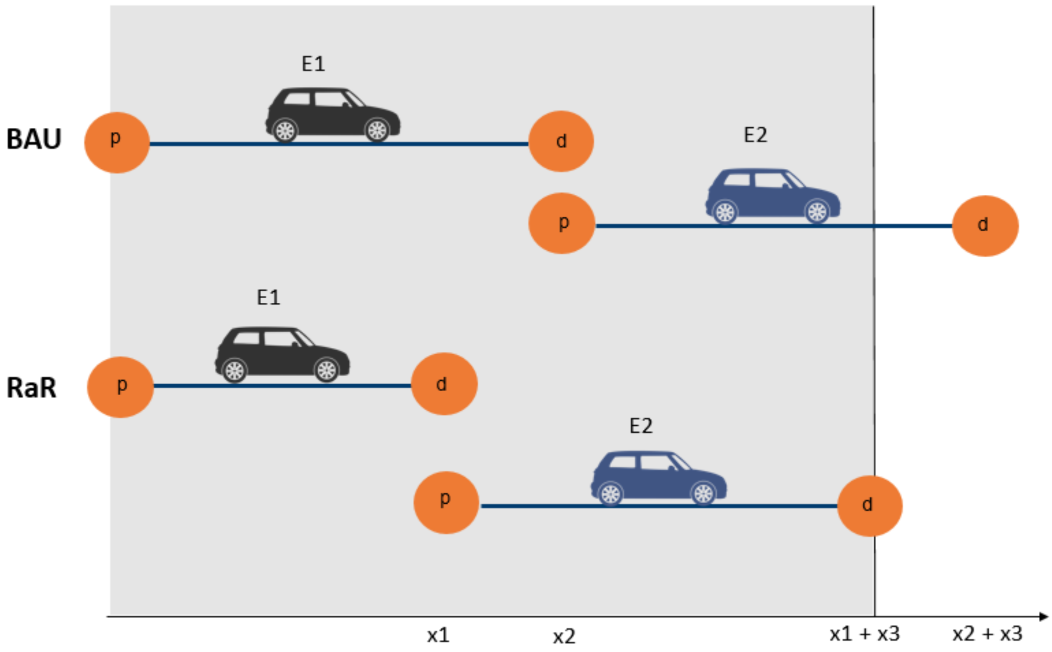

Figure adopted from Lenski et al. (2010)

Figure 2 The two scenarios considered for the quantification of environmental life-cycle burdens of scrappage programs.

The cumulative life-cycle burden of the BAU scenario is

$$(p1 + d1) + E_1 x_2 + \frac{(p2+d2)}{x_3}(x_1 + x_3 - x_2) + E_2\ (x_1 + x_3 - x_2)$$

The cumulative life-cycle burden of the RaR scenario is

$$(p1 + d1) + E_1 x_1 + (p2 + d2) + E_2\ x_3$$

The net effect of the scrappage program is expressed as

$$E_1(x_2 - x_1) - E_2\ (x_2 - x_1) - \frac{(p+d)}{x_3}(x_2 - x_1)$$

Where

x_1 – km driven at age of scrapping

x_2 – km driven at the expected lifetime (given age at x_1)

x_3 – km driven at the average expected lifetime (200’000 km per default)

$d1$ – total disposal emissions vehicle 1

d2 – total disposal emissions vehicle 2

$p1$ – total production emissions vehicle 1

p2 – total production emissions vehicle 2

E_1- total use phase and fuel chain emissions per km driven of vehicle 1

E_2- total use phase and fuel chain emissions per km driven of vehicle 2

4.1.1 Natural lifetime and years remaining

To calculate the number of years the lifetime is reduced the expected lifetime conditional on surviving a certain time period is calculated. The conditional survival function can be used to calculate the survival probabilities given that a vehicle survives until year a and is expressed as [32]:

$$P(\text{vehicle survives a further time y}|\text{vehicle survives to a}) \; = R(y|a) = \frac{R(a+y)}{R(a)}$$

Where y is years, a is vehicle age and R the survival function. The future expected lifetime of a vehicle at age a is the area below the conditional survival function $R(y|a)$.

4.2 Program description and data sources

Three different programs are evaluated. First, the Cash-for-Clunker program limited to conventional vehicles introduced in Germany in 2009. Then a hypothetical current program replacing diesel vehicles with electric vehicles and finally a similar program to be introduced in the future.

Common data sources

- **Emission factors:** these are taken from HBEFA v.3.3 for different euro classes and are valid for Germany. Average traffic situation and hot emission factors are used. NO_x and NO_2 emission factors are updated to reflect "real-world" emissions of diesel cars, and are similar to values published by ICCT [33]. Emission factors are available for three different engine sizes in HBEFA and are assigned to euro and vehicle size classes as shown in Table 12 and Table 9.

- **Life cycle inventories (LCI):** are based on earlier work at PSI [34]. To obtain inventories for older euro classes only emission factors and fuel consumption are changed, while the other inventory values are kept constant. Hence, production and disposal impacts are assumed constant. BEV are charged with the German electricity mix.

- **Estimation of shortening of lifetime:**
  - **Survival curves:** a survival curve, obtained from a study by Oguchi & Fuse (2015), is used to estimate the years remaining and is Germany-specific. The curve is also confirmed using available stock data [35]. From this the shortening of lifetime is estimated.

- **Annual kilometres driven:** three different scenarios are defined for the annual kilometres driven in the 2009 program, while the old and new cars are assumed to drive the same yearly distance in the two other programs. The yearly distance is assumed to equal the German average of 14'000 km, as stated by the most recent data from 2014 [36].

4.2.1 Cash-for-Clunker: the car replacement program introduced in Germany in 2009

The program introduced in 2009 had a budget of 5 billion euros and close to 2 million cars were exchanged. The cars scrapped had to be at least 9 years old, meaning they had an emission standard of euro 2 or earlier.

Information about cars scrapped and purchased in the program is available by brand, model and size class [37]. Additionally, the euro class of new vehicles is known and the age distribution of the scrapped cars [38].

The share of petrol and diesel cars is not available. The diesel share of the new vehicles are assumed to be 7.5% as used by Höpfner et al. (2009). The diesel share of the scrapped car are estimated by vehicle stock data from 2009 [39] and 2010 [40]. The cars leaving the stock are assumed to be scrapped. The diesel share of these cars equals on average to 11.5% for emission concepts equal to or older than euro 2. Through communication with IFEU (Ulrich Höpfner, personal communication, 11 march 2019) the diesel share is indicated to represent about 14% of the *mileage* of the scrapped cars. Using a diesel share of 11.5% of *scrapped cars* corresponds to 11.5% of mileage of the scrapped cars, if one assumes the same annual mileage or 16%, if the annual mileage is assumed to vary by vehicle age, powertrain and size.

Three different scenarios for annual kilometres driven are defined as this is identified as essential to consider by earlier studies (see section 3.3.1):

1. Old and new vehicles are driven the same yearly distance of 14’000 km
2. Annual kilometres driven are dependent on vehicle size, age and powertrain
3. New vehicles are driven more than older vehicles because of the rebound effect

4.2.2 Replace-and-Retire: hypothetical program replacing diesel vehicles for BEV

This hypothetical current program considers the introduction of a program replacing diesel vehicles with battery electric vehicles (BEV) in the 63 German cities exceeding the NO_2 limits in 2018 [41]. A program of the similar scale as the 2009 program is assumed, and thus limited to two million cars.

In line with the suggested diesel bans in many of these cities, the cars eligible for the program are diesel cars with an emission standard of euro 5 or earlier. The number of these cars and their size and euro distribution is taken from the county-level vehicle stock data from KBA [42]. Only 59 out of the 63 cities are considered, as data lacks for the others.

The size of the new BEVs is approximated using a report on the BEVs purchased under the current subsidy program in Germany [43]. Similar to what is seen from the available data from the 2009 program, a downsizing effect is assumed.

The average age is calculated as the program introduction year minus the average introduction year of the emission standard. The legislation introduction years are shown in Table 10.

- **Inconsistency between HBEFA and car model results with WLTC driving cycle**: the German specific fuel consumption of conventional vehicles (ICEV) in HBEFA v.3.3 is lower than estimated by PSI’s car model using the WLTC driving cycle. To overcome this, the BEV electricity consumption in PSI’s car model is reduced by the relative difference between the fuel consumption in HBEFA and the estimation by PSI’s car model for ICEV.

4.2.3 Potential future program for introduction of electric vehicles

A potential future program in 2030, similar to the current Replace-and-Retire program, is then considered using a simple prediction of the 2030 conventional vehicle stock in the 59 cities.

The stock is predicted assuming that:

- Diesel share and vehicle ownership rates stay constant. Hence, all diesel vehicles leaving the current stock are assumed to be replaced by a diesel vehicle.
- The euro 6d standard is valid between 2020 and 2030, and all new vehicles therefore have an emission standard of euro 6d.

The prediction of the stock for 2030 is done by the conditional survival curve used for the 2020 program. The output from the 2020 stock of each euro class is then predicted and the sum of vehicles leaving the stock is replaced by euro 6d vehicles. The size distribution of old and new cars is similar to the current program.

The values for the LCI of 2030 BEVs are the average of the current and future cars, applying linear interpolation between 2020 and 2040, modelled in [44]. The electricity consumption is reduced to be in line with the lower fuel consumption of conventional vehicles in HBEFA.

The future scenario for energy supply is generated by the REMIND integrated assessment model and the scenario limiting the remaining carbon budget to 950 Gt CO_2-eq. is used. The electricity markets in ecoinvent are then modified. The marginal supply mix is calculated as detailed in Vandepaer *et al.* (2018), using 2030 as a reference year and a 10 year time horizon.

Table 1 Overview and data sources for important parameters.

	Age	**Size**	**Euro class**	**Mileage**	**Lifetime reduction**
2009 program	Age distribution of exchanged cars	Data on exchanged cars	Age distribution (clunkers) Data on exchanged cars (new)	3 scenarios defined	Survival curve
Current program	Introduction year of legislation	Vehicle stock data Report on BEV subsidy program	Vehicle stock data	Equal mileage	Survival curve
Future program	Introduction year of legislation	Same as for current program	Stock projection	Equal mileage	Survival curve

4.3 Human health impacts

The regional Replace-and-Retire program is also assessed considering the trade-off between local benefits to human health and increased human health impact caused by indirect emissions elsewhere.

The impact on human health from savings in direct emissions and increase in indirect emissions is quantified in disability-adjusted life years (DALY) using characterisation factors.

$$CF = iF * EF * DF$$

Where

$$iF = XF * FF$$

Where,

XF is the exposure factor, FF the fate factor, EF the effect factor, iF the intake fraction and DF the damage factor.

The intake fractions describe the inhaled mass by the population to the mass emitted of a pollutant. They combine the exposure factor, expressing inhalation, with the fate factor, expressing transport and removal of the substance from the air. These are then multiplied with the effect and damage factor to quantify the effect of the inhaled mass.

For impacts of particulate matter formation city-specific intake fractions for PM2.5 for some of the cities involved in the hypothetical BEV program are available from Fantke *et al.* (2017). The intake fractions for emissions outdoor, urban at ground level, are used. To arrive at city-specific characterisation factors, the intake fractions were multiplied with the effect and damage factor for Germany of 285.74 years per kg intake from van Zelm *et al.* (2016). For the cities were no intake fractions are available, the average of the known iFs is used[2]. This corresponds to a value between the values for a non-city specific German average and the average European city.

For secondary particulate matter (NO_x, SO_2, NH_3) CFs for Germany from LC-impact are used, and no differentiation between emission source locations can be made. For indirect emissions the global average CFs from LC-impact are used, as the emission locations are unknown. For health impacts of photochemical oxidant formation, the German specific CFs from LC-impact are used for direct emissions, while the global average CFs are used for indirect emissions of NMVOC and NO_x.

As seen in Figure 3 the difference between intake fractions is considerable. The lowest and the highest intake fractions are found for Koblenz and Essen, respectively. The intake fraction for Essen is almost 15 times as high as the one for Koblenz.

Table 2 CF used for LCIA. All in DALY/kg emitted.

	Location	PM2.5	NH3	NO_x	SO2	NMVOC	Reference
PMF	Germany	City-specific 4,25E-03	4,82E-04	1,70E-04	1,66E-04		[46], [47]; LC-impact
	Global	6,29E-04	1,61E-04	7,62E-05	1,83E-04		LC-impact
POF	Germany			6,93E-08		2,46E-07	LC-impact
	Global			9,10E-07		1,40E-07	LC-impact

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[2] Except for the Rhine-Ruhr area where the Essen CF is applied

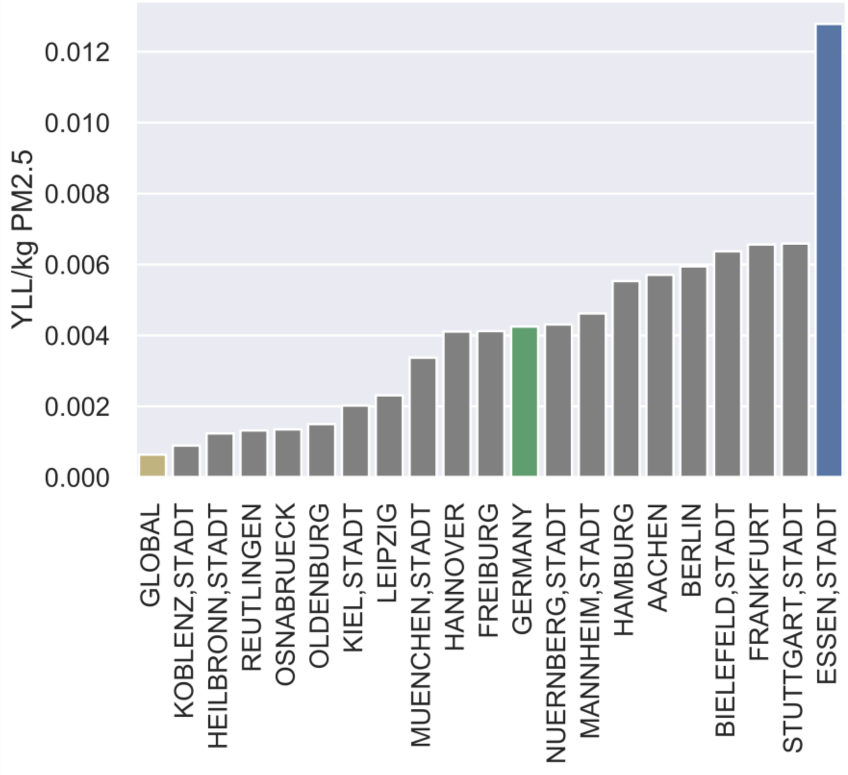

Figure 3 City-specific characterisation factors for PM2.5. "YLL": Years of Life Lost.

5 Results

5.1 Life-cycle impacts of scrappage decision

The LCA results for different powertrains and euro classes are here shown as a function of time. At time zero one can decide to either purchase a new vehicle (with a newer emission standard/technology) or keep driving the old one. If the line of the old car crosses the line of the new car, replacing the old car will lead to environmental benefits as the use phase emission reduction is high enough to offset the increased production and disposal emissions after a certain number of kilometers.

Most clunkers in the old German scrappage program were small petrol cars with emission standard euro 1, while most new cars had a euro 4 emission standard. The left panel in Figure 4 shows that replacing a euro 1 petrol cars with a euro 4 petrol car will not reduce overall GHG emissions. Replacing a petrol car with the oldest emission standard with a euro 4 petrol car would yield benefits in terms of GHG emissions. Exchanging a pre euro 0 or a euro 1 car will yield lower photochemical oxidant formation impacts (Figure 5).

In the hypothetical current program diesel vehicles are replaced with BEV. As seen in Figure 4 (right panel), replacing a diesel vehicle would offset the GHG emissions from production and disposal emissions if the long-term marginal electricity mix is used for BEV charging. Marginal electricity mixes are quantified according to [45]. Photochemical oxidant formation impacts (mostly due to NO_x and NMVOC emissions) would be reduced independent of the electricity mix (Figure 5).

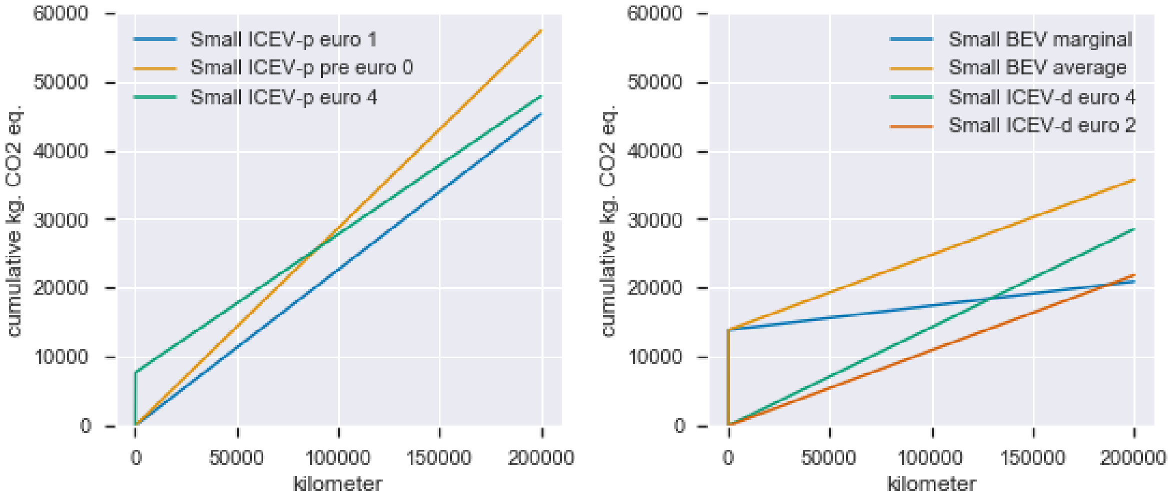

Figure 4 Cumulative GHG emissions of different powertrains and emission standards for a small vehicle. Electricity mixes for charging BEV are German average and long-term marginal mixes.

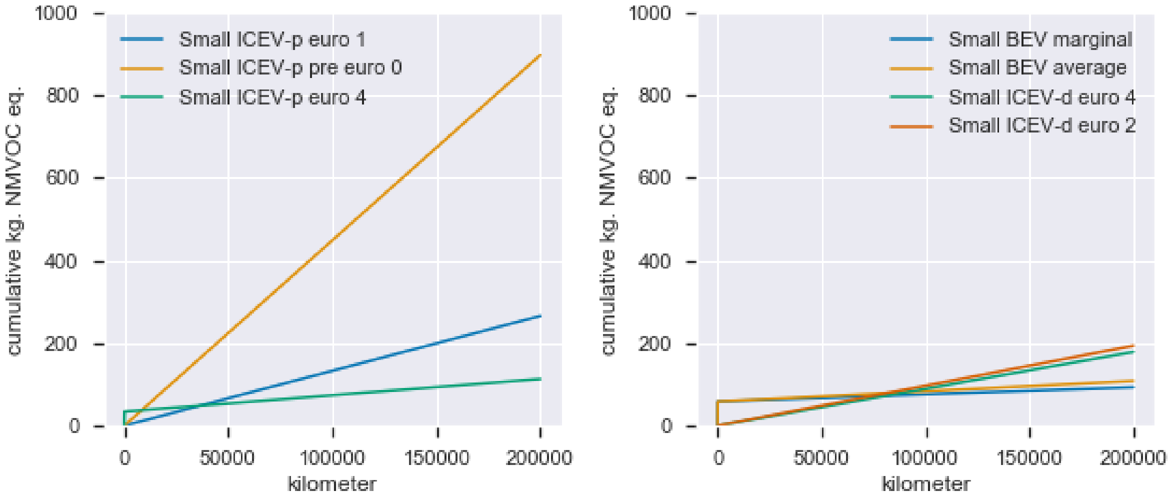

Figure 5 Cumulative photochemical oxidant formation impacts of different powertrain and emission standards for a small vehicle. Marginal and average refers to the German electricity mix used for charging.

5.2 Cash-for-Clunker

The size of the exchanged vehicles through the past program in Germany is shown in Figure 6. Similar to earlier assessments of scrappage programs [22]–[24], an increase in the small size segments is seen. Cars scrapped were mostly euro 1 or euro 2, while new cars were mostly euro 4. The average age of the old vehicles was 14 years. The estimated reduction of lifetime is 3.98 years, which is similar to high estimates from the program in the US, but is reasonable as the number of very old cars were lower in Germany than in the US [31].

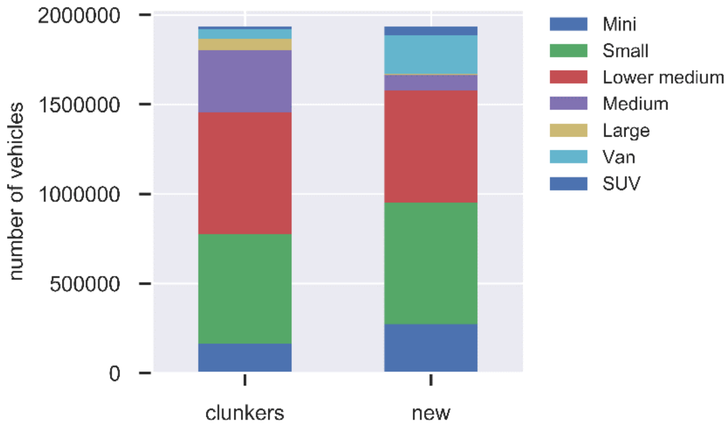

Figure 6 Size of old and new vehicles exchanged under the program in 2009. Shares of vehicles in the mini, small and van categories increased, while other categories decreased.

Results for different life-cycle impact categories are shown as a function of average years remaining and mileage scenarios in Table 3.

Table 3 Life-cycle impacts of program for different reduction in lifetime and scenarios for kilometres driven. CC impact given in Mt CO2-eq., POF impacts in Mt NMVOC-eq. and PMF in Mt PM-eq. Negative values correspond to emission savings, positive values increased emissions.

	Scenario 1			**Scenario 2**			**Scenario 3**		
Average reduced lifetime	CC	POF	PMF	CC	POF	PMF	CC	POF	PMF
3,98	1,5	-0,08	-0,006	3,4	-0,04	-0,0005	1,9	-0,08	-0,005
2,98	1,3	-0,05	-0,004	2,6	-0,03	-0,0001	1,6	-0,05	-0,003
1,98	1,0	-0,03	-0,002	1,8	-0,02	0,0003	1,2	-0,03	-0,002

Decreasing the reduction of lifetime decreases savings in photochemical oxidant formation (POF) and particulate matter formation (PMF) impacts. At the same time, the increase in GHG emissions is reduced. If the years remaining for the clunkers are reduced by 2 years, to an average of 1.98 years, the increase in GHG emission is 35% lower than for the almost 4 years earlier retirement scenario. Savings in impacts related to POF and PMF are reduced by 63% and 69%, respectively. In scenario 2, new cars are driven on average 10% more than old cars, which increases GHG emissions and decreases *savings* in POF and PMF impacts.

Figure 7 shows the impact of the program if considering an average lifetime reduction of 3.98 years and an annual mileage of 14’000 km for both the old and new cars. This program yields an increase in life-cycle GHG emissions. POF and PMF impact decreases as the reduction in the use phase are large enough to offset increased production and disposal emissions. The fuel economy improvement is not large enough to offset the increase in GHG emissions from production and disposal. GHG emissions increase by 7% compared to the BAU scenario, while POF and PMF impacts decrease by 52% and 13%, respectively.

The effect on GHG emissions and PMF is sensitive to the assumed lifetime of the second vehicle. Increasing the lifetime of the second car to 225’000-235’000 km instead of 200’000 km leads to a net zero effect on GHG emissions. If the lifetime is reduced to 175’000-185’000 km, the program would have a net zero effect on PMF.

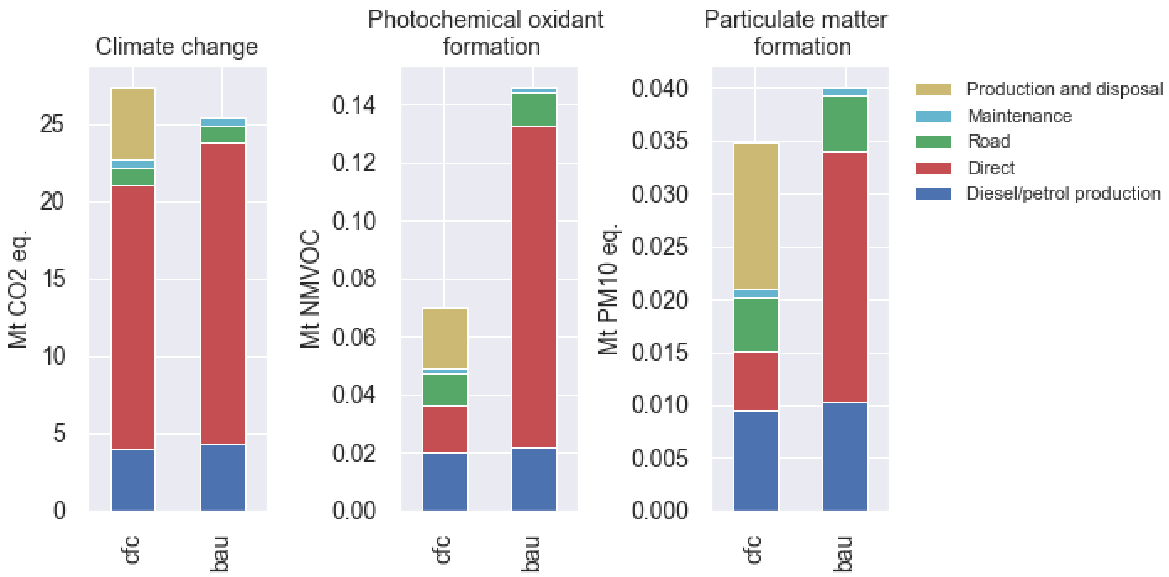

Figure 7 Life-cycle impact results on climate change, photochemical oxidant formation and particulate matter formation of the two different scenarios: cfc where the scrappage program is introduced, and business as usual (bau).

The downsizing effect induced by the program causes a lower increase in GHG emissions. If no downsizing effect would be present, the increase in GHG emissions would equal 2.2 Mt CO_2-eq instead of 1.54 Mt CO_2-eq. Conversely, the decreasing diesel share (of old versus new cars) rises GHG emissions. If the diesel share instead would be the same for the scrapped and new vehicles, the increase in GHG emissions is only 1 instead of 1.54 Mt CO_2-eq.

Figure 8 shows the effect on air pollutants when a program reducing car lifetime by 3.98 years on average is introduced and mileage of the old and new cars are the same. Direct emissions of NO_c, NH_3 and NMVOC are reduced enough to compensate for increased indirect emissions. Conversely, indirect emissions of PM2.5, PM10 and SO_2 increases significantly and the life-cycle emissions of these pollutants increase. Hence, the reduction in overall PMF impact is caused by the large reduction in NO_x, as well as NH_3 emission reductions, which are precursors of secondary PMF.

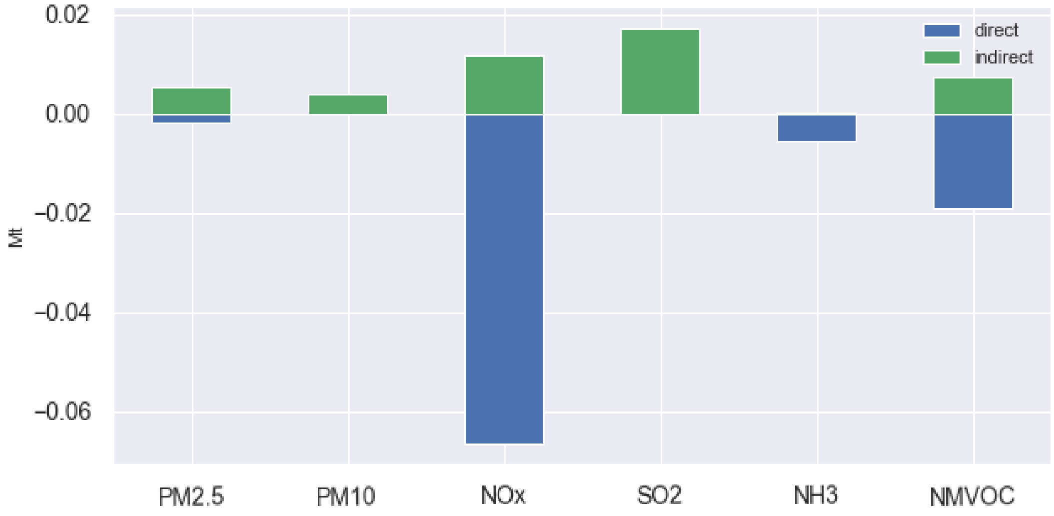

Figure 8 Difference in air pollutant emissions between the two scenarios. Indirect emission increases, while direct emissions are reduced in the cfc scenario.

As seen in Table 4, a shorter lifetime reduction yields lower direct emission savings. On the contrary, the increase in direct emissions of PM2.5, PM10 and SO_2 will be lower.

Table 4 Changes in air pollutant emissions due to scrappage program in kT. Negative values correspond to emission reductions, positive to emission increase. Scenario 1 and 2 refer to different mileage assumptions.

Mileage scenario	Avg. lifetime reduction	PM2.5	PM10	NOX	SO2	NH3	NMVOC
Scenario 1	3,98	3,4	4,0	-55,2	16,6	-5,1	-12,0
	2,98	2,6	2,6	-38,7	12,5	-4,1	-7,3
	1,98	1,8	2,0	-22,2	8,4	-3,0	-2,7
Scenario 2	3,98	2,9	3,5	-31,5	16	-3,1	-5,5

The effect on air pollutants is similar to results found by Lenski, Keoleian and Bolon (2010) for CARS: life-cycle emissions of PM and SO_x increase, while NO_x emissions decrease. This is also in line with earlier studies finding that shortening vehicle lifetime increases NO_x emissions. Fraga (2011) estimate a reduction in *direct* emissions of 32 kT NO_x for the German scrappage program. In this study updated NO_x emission factors are used and a higher estimate of direct emission savings of about 55 kT is estimated, which is in the same range as found in the US.

Past studies of specific scrappage programs have found minor reductions or neutral effects on GHG emissions, while several other studies find GHG emission increase when vehicle lifetime is reduced. Hence, the effect on GHG emissions is clearly uncertain. Lenski, Keoleian and Bolon (2010) estimated GHG emission savings of 4.4 Mt CO_2-eq for CARS in the US which involved 700’000 cars. Several factors can explain the difference between the results. First, the clunkers in the US were older than the German ones and the emissions and fuel consumption generally higher. Second, in the US many light trucks (with poor fuel-economy) were exchanged for passenger cars with a better fuel-economy. The improvement in average fuel economy was about 25% in the US (15.8 miles/gallon to 25 miles/gallon

[15]), while the fuel economy improvement used in this study for Germany is 11% (from 54.9 g/km to 49.5 g/km). This lead to larger savings in direct emissions and fuel chain emissions in the US compared to Germany. The improvement in fuel economy in the German case was estimated to be 20% by Höpfner, Hanusch and Lambrecht (2009). Also Kagawa *et al.* (2013) assume a more substantial improvement in fuel economy of 25% from a Japanese scrappage scheme.

Additional factors contributing to divergent results are that the years before natural disposal considered in the US study were shorter and the annual distance driven considerably higher. Lenski, Keoleian and Bolon (2010) also assumed that all vehicles, independent of age, would be scrapped after 2.52 years. In this study, the reduction in lifetime is supposed to depend on age. Hence, the oldest cars (pre euro 0 and euro 0) contribute less to direct emission reductions than in the study by Lenski, Keoleian and Bolon (2010) and the savings in direct emissions are therefore less prominent.

5.3 Hypothetical BEV scheme today

The cars exchanged by size is shown in Figure 9. As for the 2009 program, a downsizing effect is assumed. The shares of euro 4 and euro 5 cars are high and the average age of replaced cars is 12.4 years. The reduction of car lifetime is estimated to 5-6 years, depending on the euro distribution in each German county.

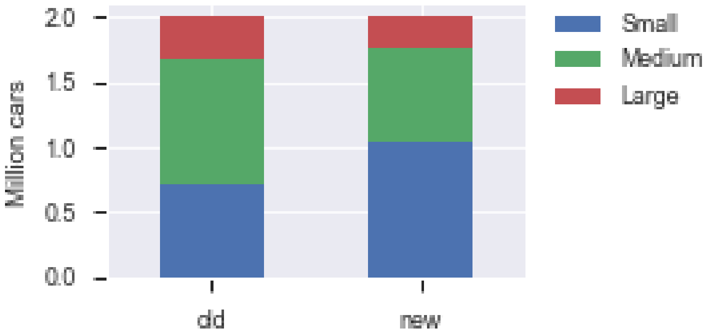

Figure 9 Size of diesel vehicles (old) and BEV (new) exchanged.

Figure 10 shows the effect of the Replace-and-Retire program on climate change, photochemical oxidant formation and particulate matter formation. Results are shown both with an average and marginal German electricity mix for BEV charging; The current average German electricity mix has a CO_2 intensity of 580 g CO_2 eq./kWh and the long-term marginal one of 130 g CO_2 eq./kWh. Considering the average current German electricity mix for charging, GHG emissions increase. This is caused by the high CO_2 intensity of the current German electricity mix, as well as the energy demand for BEV production. Considering the marginal German mix GHG emissions decrease.

Both Replace-and-Retire scenarios lead to reduction in photochemical oxidant formation, as the reduction in direct NO_x emissions is large enough to compensate for increased indirect emissions. Conversely, both scenarios have a net negative effect on particulate matter, being a consequence of the high emissions during the production phase of BEV. Mining activities as well as electricity production from coal are the top contributors to these emissions.

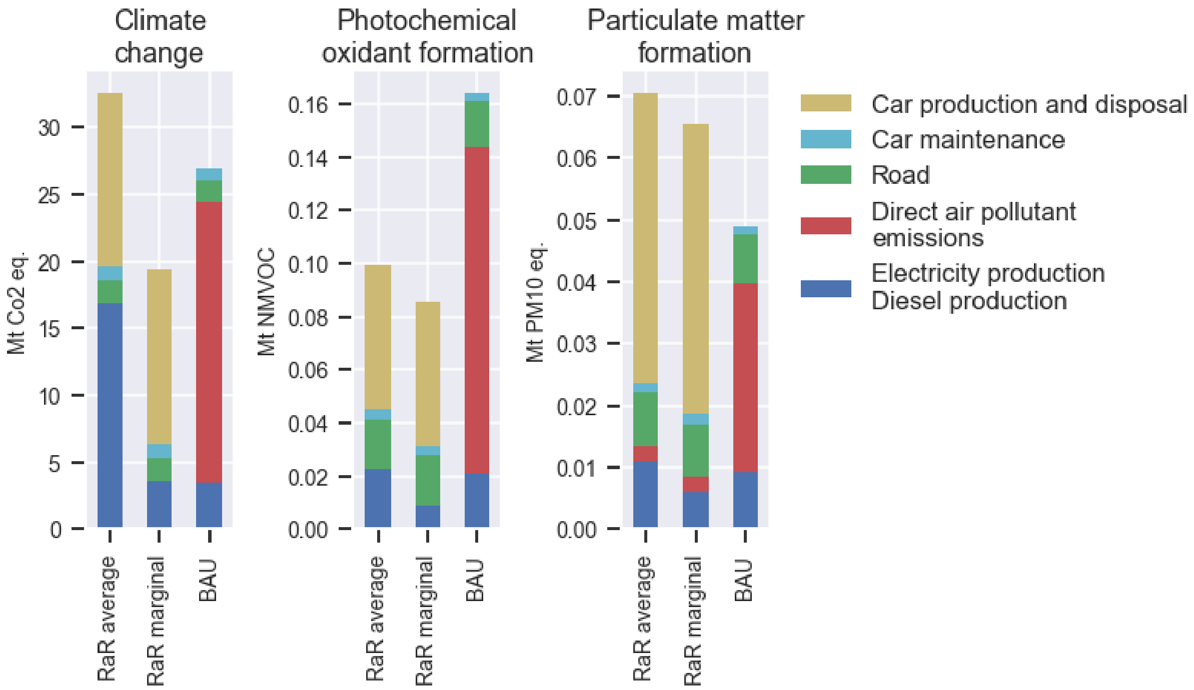

Figure 10 Life-cycle results for climate change, photochemical oxidant formation and particulate matter formation. CFC indicated the Cash-for-Clunker scenario, while BAU indicated business-as-usual (driving the clunkers in the program period).

Table 5 Effect on impact categories from the BEV program.

Years	Electricity mix	CC	POF	PMF
5-6 years	Average	5,6	-0,06	0,022
	Marginal	-7,6	-0,08	0,016

As for the 2009 program the results are sensitive to the years remaining and the annual mileage assumed. If the lifetime of all diesel cars is reduced by only 1 year instead, the increase in GHG emissions is 1 Mt CO_2 considering the average electricity mix. NO_x savings are reduced by 82%.

The effect on GHG emissions and PM emissions are not as sensitive to the assumed lifetime of the second vehicle as in the conventional (past) vehicle program. Using the average electricity mix the lifetime of the second vehicle is about 800’000 km and 400’000 km before the program has a neutral effect on GHG emissions and PM emissions, respectively.

The program reduces direct emissions of all air pollutants and therefore yield benefits to local air quality. When also considering indirect emissions only NO_x emissions decrease, while life-cycle emissions of all other air pollutants increase. As diesel cars are replaced instead of petrol cars, NH_3 and NMVOC emissions are increased, contrary to what was seen in the 2009 program.

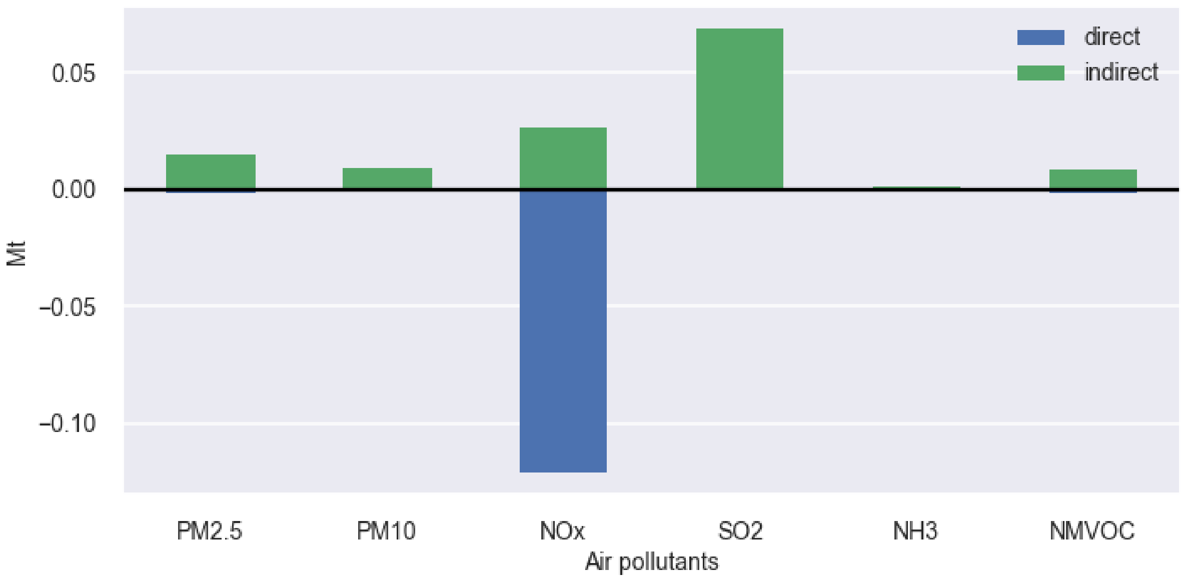

Figure 11 Effect on air pollutants (marginal electricity mix).

Main processes contributing to the indirect emissions of air pollutants are shown in Table 6.

Table 6 Top contributing processes to indirect air pollutant emissions.

	Average electricity mix	Marginal electricity mix
PM2.5	Electricity production from lignite and hard coal Diesel burnt in building machine Road wear emissions	Electricity production from lignite and hard coal Coking
PM10	Road construction Iron mine operation Lignite mine operation Road wear emissions	Road construction Iron mine operation Road wear emissions
NOx	Diesel for building machine Electricity production from lignite Sea transport Mine operations (blasting) Train transport	Diesel for building machine Mine operation (blasting) Sea transport Electricity production, hard coal
NH3	Anaerobic digestion of manure Mine operation (blasting)	Mine operation (blasting) Zinc coating Anaerobic digestion of manure
NMVOC	Road construction Glider production	Road construction Glider production
SO2	PGM mine operation Nickel mine operation Copper production Electricity production from lignite	PGM mine operation Nickel mine operation Copper production

5.3.1 Impact on human health

Differentiating the impact of air pollutant emissions by location is essential. Direct emissions occur in urban city centres where the impact of emission typically is high. Indirect emissions may occur both within and outside Germany, as well as outside urban areas. Hence, the impact of emissions, and not only mass, should be considered.

Lower tailpipe emissions cause a reduction in human health impacts of 27’300 DALYs. The health burden of particulate matter emissions was estimated to 547’828 DALYs in Germany in 2016 [48], so the health impact reduction of about 5000 DALY per year account for 1% to total burden from particulate matter in Germany. Assuming that all indirect emissions have a human health impact equal to the global average yields life-cycle impact *reductions* of 60 and 3000 DALYs considering the average and marginal charging electricity mix, respectively.

The human health impact reduction from decreased direct emissions are most prominent in larger cities (Berlin, Hamburg, Hannover, Munich) where the highest number of cars is exchanged. If divided by the number of cars exchanged in each county the health impact reduction is largest in the Rhine-Ruhr area, followed by Berlin, Hamburg, Stuttgart, Bielefeld and Frankfurt.

If the human health impacts are allocated to the counties initiating the demand for new cars, Stuttgart, Berlin, Hamburg and the Rhine-Ruhr area are counties with decreased human health impacts from implementation of a scrappage program when the average electricity mix is assumed for charging. If the marginal electricity mix is considered, human health impact is reduced in all counties except Heilbronn, Reutlingen, Munich, Oldenburg, Osnabruck, Koblenz and Leipzig. As shown in Figure 3, these are cities were the CF is lower than the German average and the reduced health damage from direct emissions are therefore not enough to compensate for the increased indirect emissions.

When human health impacts are divided by the number of cars exchanged in each county, the impact reduction is most noticeable in the Rhine-Ruhr area. The intake fraction is substantially higher in Essen than in other cities since the population density is high and the topography gives rise to frequent inversion layers trapping air pollution [49].

In addition to the number of cars exchanged and the city-specific CF, differences in euro and size distribution lead to differences between the counties.

5.4 Future program

The projected diesel vehicle stock in 2030 in the 59 cities is compared to the current stock in Figure 12. Of the 2 million cars to be replaced in 2030, 18% are euro 5 vehicles, 65% euro 6 and 13% euro 6d. The average reduction in lifetime is 5 years and a mileage of 14’000 km is assumed for both old and new vehicles.

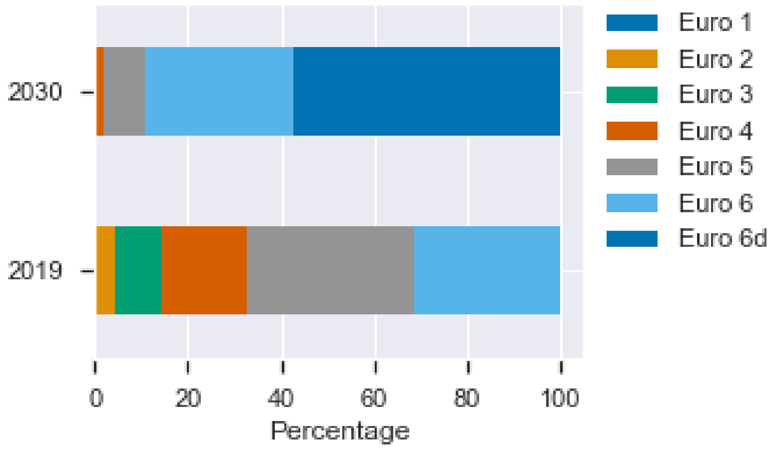

Figure 12 Projected diesel vehicle stock in 2030 compared to current stock.

The life-cycle impacts of implementing a future program are shown in Figure 13. As seen in Table 8, the 2030 future electricity mixes under a climate change mitigation scenario have a substantially lower GHG intensity compared to current mixes. As a consequence, a future scrappage program will under this climate change mitigation scenario reduce life-cycle GHG emissions both when the average and marginal mix is used for BEV charging. As for past programs, photochemical oxidant formation impacts decrease, but the reduction is lower than for the current BEV program. This is because nearly 80% of the cars to be replaced have emission standard euro 6 or 6d, which have 45% and 90% lower NO_x emissions than euro 5 cars, respectively. Despite the lower share of fossil fuels in the electricity generation mixes, particulate matter formation impacts from BEV production still offset the decrease in tailpipe emissions.

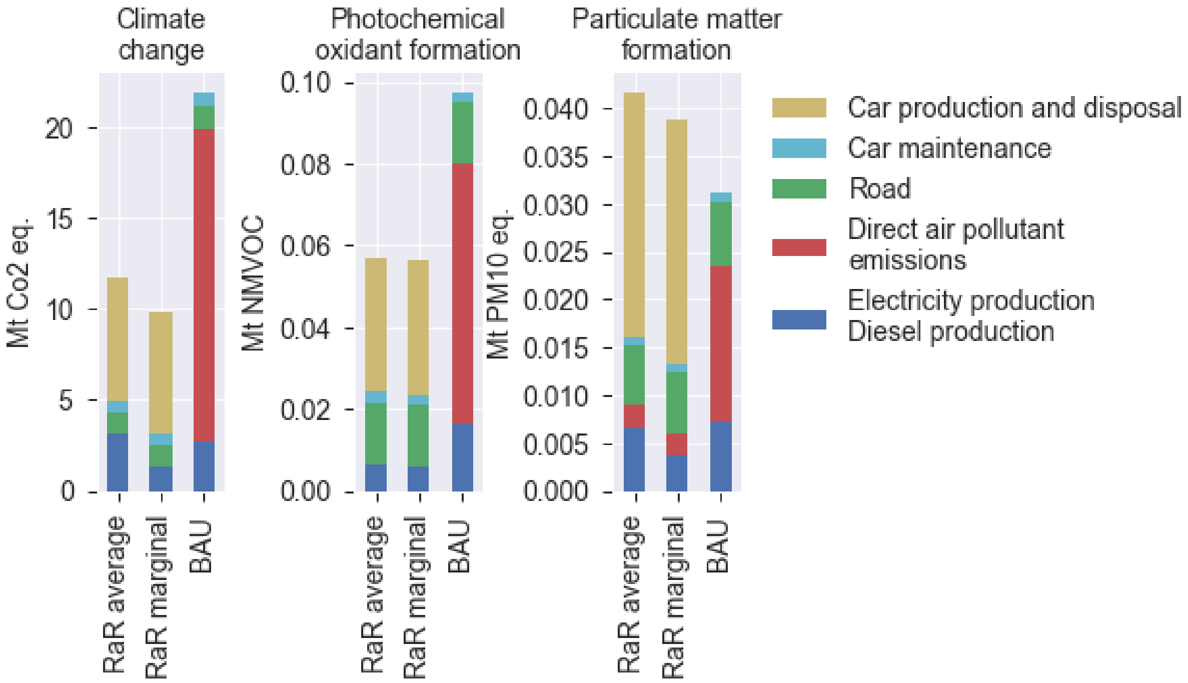

Figure 13 Life-cycle impacts of BAU and RaR scenarios for a hypothetical retire-and-replace program implemented in 2030.

Table 7 Life-cycle impact results of the future retire-and-replace program (in Mt).

	CC	**POF**	**PMF**
Average electricity mix	-10.2	-0.04	0.01
Marginal electricity mix	-12.1	-0.04	0.008

Table 8 GHG intensity of electricity mixes today and in 2030 under a climate change mitigation scenario. All values in g CO_2-eq./kWh.

	Current average	**2030 average**	**2030 marginal**
Electricity mix, low voltage, DE[3]	580	125	52
Electricity mix, medium voltage, GLO[4]	737	209	

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[3] Used for BEV charging; due to lack of a Germany-specific electricity mix from the REMIND model, a EU-mix has been used for calculations instead.

[4] Used for battery cell production

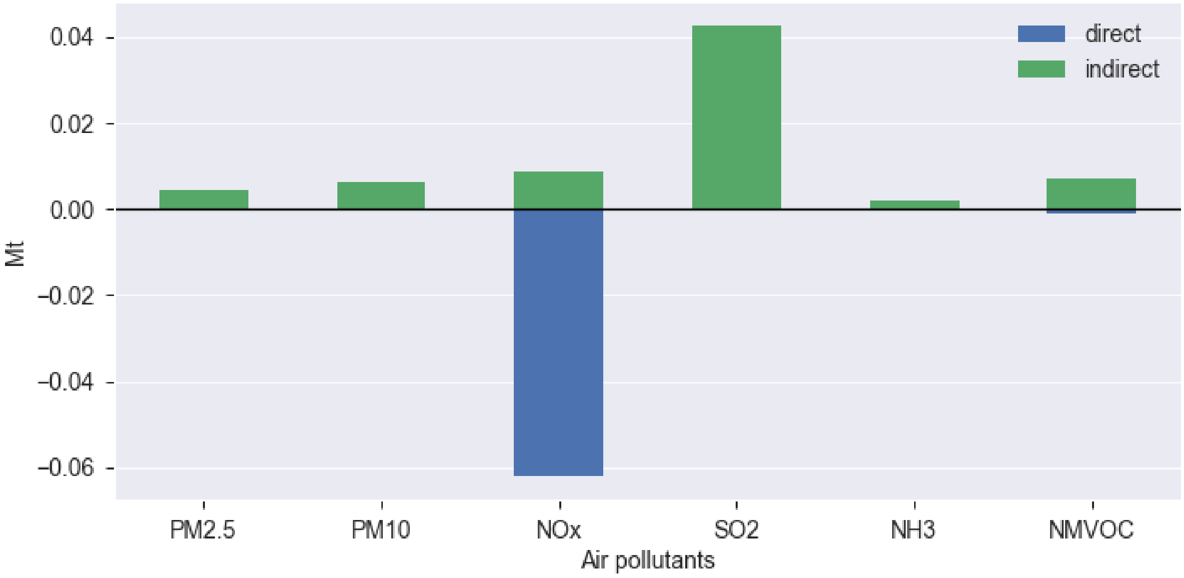

Figure 14 Air pollutant emissions of the future retire-and-replace program (marginal electricity mix for BEV charging).

Compared to the current BEV program, savings in direct emissions are lower for all air pollutants. Savings in direct PM emissions are 82% lower and NO_x emissions 50% lower in the future program. As the share of fossil fuels in the electricity mix will decrease in general, the increase in indirect emissions is also lower. As a consequence, NO_x life-cycle emission savings and life-cycle emissions increase of other air pollutants (except NH_3) is lower.

Reduction in human health impact due to decreased tailpipe emissions amount to 11’800 DALYs, compared to 27’300 DALYs for the current program. As for the current BEV program all indirect emissions are assumed to have a human health impact equal to the global average. The program will then lead to an *increase* in human health impacts by 1145 DALYs, if the average electricity mix is used for BEV charging. Conversely, if the marginal electricity mix is used, the program *reduces* human health impacts by 106 DALYs. Hence, if the impact of emissions in future are equal to current impacts, human health benefits are lower in a future program than today. This is because many euro 6 and euro 6d cars replaced. If a national-wide program of the same size was implemented instead, almost all cars replaced would have an emission standard of euro 5 or earlier (Figure 15). The potential savings in direct emissions would then be higher, but the reduction in human health impact may be lower as the program is not limited to urban areas.

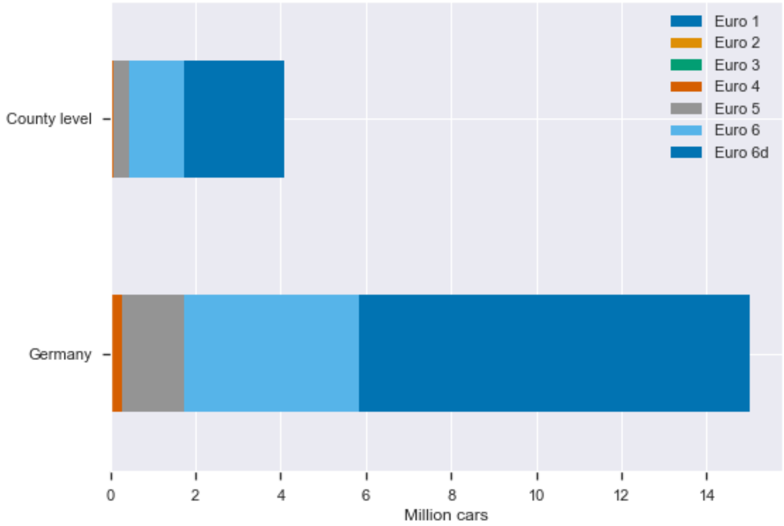

Figure 15 Projected diesel vehicle stock in Germany and the 59 counties in 2030. If the two million oldest vehicles are replaced, most cars would have an emission standard older than euro 6, if a national-wide program was implemented. If the program is limited to the 59 cities instead, mostly euro 6 vehicles would be replaced.

5.5 Comparison of evaluated programs

Figure 16 shows the effect on life-cycle emissions of introduction of different past, current and potential future scrappage schemes.
All programs yield benefits for local air quality due to reduction of direct exhaust emissions, while indirect emissions increase due to an increase of emissions associated with production and disposal of vehicles. The reduction in direct NO_x emissions is large enough to offset the increase in indirect emissions, while overall PM and SO_2 emissions increase.

Comparing this assessment of the German 2009 program to the assessment of the program in the US by Lenski et al. (2013), the conclusion on NO_x, PM and SO_2 emissions is the same. The estimated effect on GHG emissions diverge and are more uncertain. The main reason for this is the different fuel economy improvements due to the schemes. While Lenski et al. (2013) find a fuel economy improvement of 25%, the improvement estimated in this study is 11%. Additionally, the assumed lifetime reduction and annual kilometres driven can explain the different results.

The programs replacing diesel vehicles with BEVs have more substantial effects on air pollutants and GHG emissions compared to the conventional vehicle program from 2009. While NO_x emission reductions are higher, PM and SO_2 emissions increase more. The potential for NO_x emissions savings, both considering only direct and life-cycle emissions, is largest for the current BEV program as cars with higher NO_x emissions are replaced. Conversely, the increase in life-cycle PM emissions are lower in future than today.

For the current scheme, the effect on GHG emissions depends on whether the average or marginal electricity mix is considered for BEV charging. In the future, assuming decarbonisation of electricity production, introducing a program will have positive effects on GHG emissions both considering the average and marginal electricity mix. The GHG emission reduction of the future program corresponds to a one time reduction equal to 7.4% of annual GHG emissions from the German transport sector [50], if considering the marginal electricity mix. Similarly, the GHG emission reduction of the current program is 4.4% of annual transport GHG emissions.

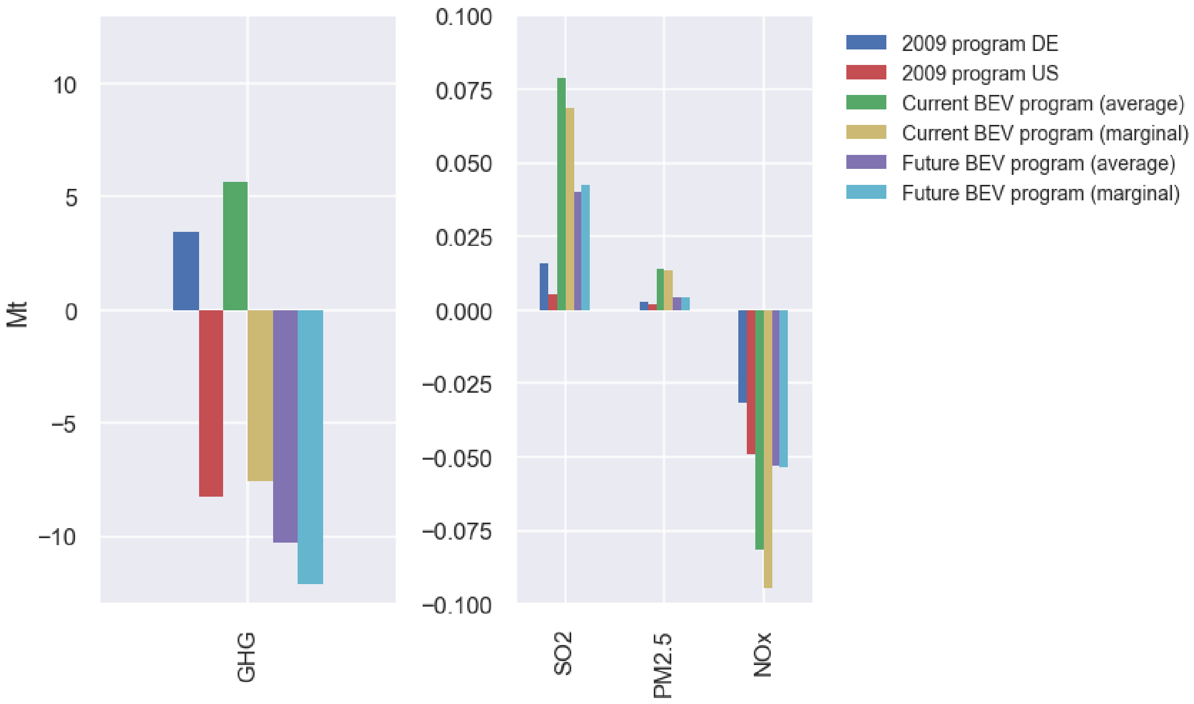

Figure 16 Effect on life-cycle emissions from introduction of different scrappage programs. Current BEV programs refer to the hypothetical German program replacing diesel vehicles with electric vehicles. Future BEV programs to a similar program in future. The 2009 program in Germany (DE) refers to the "Abwrackprämie", while the 2009 program US shows the results from the assessment of CARS by *Lenski, Keoleian and Moore (2013)*. The results for the program in the US are scaled with the difference in the number of cars to the German program (ca. 2 million cars).

6 Conclusions

6.1 Limitations and future work

As noted by earlier studies, a range of factors influence the environmental performance of scrappage program. Annual kilometres driven and the reduction of vehicle lifetime are important parameters where limited data is available for the German 2009 program. This leads to uncertainty regarding the effect of the program. Moreover, in this study we evaluate the effect of replacing close to 2 million old vehicles without considering sales that would occur in absence of the program or that were pulled forward in time. Incorporating these effects would lower the impact of the program, as these sales amount to about 1 million [23]. We also assume that the program has no effect on the second car purchased. Lenski, Keoleian and Bolon (2010) state that cars purchased under the US subsidy program had a better fuel economy than in absence of it and find this to be important for the overall life-cycle performance of the program. Additionally, we do not consider that the second car purchased in the BAU scenario occurs later in time and a more stringent emission standard could then be in place.

During the years between natural and early disposal electricity mixes and tailpipe emissions of cars are assumed constant. Static electricity mixes cause an overestimation of the impact of the BEVs in this period if the share of fossil fuels is decreasing. Tailpipe emissions tend to increase with vehicle age, so by using a fixed value, the emissions of these old vehicles and thereby the direct emission savings may be underestimated. Chen and Borken-Kleefeld (2016) find that NO_x emissions of diesel vehicles with emission standard euro 2 and euro 3 increases by 22% and 10%, respectively, over 80'000 km, while no deterioration is found for euro 1 and euro 4.

The quantification of human health impacts here assume that indirect emissions have an impact equivalent to the global average. Hence, emissions in electricity and diesel production, car production and maintenance all have the same impact irrespective of the location. Locating these emissions and their corresponding impact is essential to improve the understanding of trade-offs between benefits to local air quality in Germany and drawbacks elsewhere. Moreover, city-specific CFs are only applied for PM2.5 emissions. If city-specific impacts were available for other air pollutants the regional assessment could be improved.

Other limitations concern the following issues, which should have minor effects on the results:

- The same survival curve (from 2008) was used for past, current and future programs. In reality, there might be temporal changes in lifetime distributions [52]. However, between 1999 and 2010 the German average vehicle lifetime was stable.
- Only the fuel consumption and direct air pollutant emissions of the older euro classes were modified, while the rest of the inventory is taken from a “euro 6” car.

6.2 Conclusions

The German vehicle scrappage program implemented in 2009 caused a neutral to moderate increase in life-cycle GHG emissions, as the fuel economy improvement was modest. Direct emissions of all air pollutants decreased, but only the decrease in NO_x, NH_3 and NMVOC emissions was large enough to compensate for increased vehicle production and disposal emissions. Introducing a program directed towards electric vehicles today could reduce tailpipe NO_x emissions more substantially than the past program. A similar program in 10 years from now would cause lower NO_x emission savings than a current program, as a large share of the vehicles to be replaced would have a new emission standard. Savings in tailpipe particulate matter (PM) emissions are modest from all programs. Life-cycle PM emissions will rise, especially if a diesel scrappage program is introduced in order to switch to BEV, as PM emissions caused by BEV production are relatively high. Determining the location and the associated human health impacts of these emissions is essential to ensure that health burden is not shifted from urban areas in Germany to elsewhere in the global supply chain.

A current program in the cities with the highest NO_2 concentrations in Germany would benefit human health in these cities. A program implemented in the Rhine-Ruhr area would be particularly effective, as the human health impact of $PM_{2.5}$ emissions is considerably higher there than in Germany on average. However, the increased indirect emissions pose increased human health impacts outside the urban areas. Considering that these emissions have a human health impact equal to the global average and that the German average electricity mix is used for BEV charging, the net human health effect of the program is still positive in the Rhine-Ruhr area, as well as in Stuttgart, Berlin and Hamburg.

Programs directed towards electric vehicles can in addition to reduction in NO_x emissions and local human health burden bring benefits to climate change mitigation and have larger potential to do so than scrappage programs limited to conventional vehicles. However, this can only be realised if the additional energy demand for charging is met by an electricity mix considerably cleaner than the current German one.

NO_x emissions are most effectively reduced if the period before natural disposal is longer. As NO_x emissions have not decreased substantially for small diesel cars, replacing cars with an emissions standard of euro 4 or euro 5 will yield higher NO_x emission savings than replacing an older car. This is because the period with tailpipe emission savings is longer and NO_x emission contributions from the production phase are small. However, this comes at the expense of higher PM and SO_2 emissions. If the average German electricity mix is used for charging, the increase in GHG emissions is higher, if newer cars are replaced. This trade-off between decrease in NO_x emissions and increased GHG emissions can be avoided if coal power is phased out quickly and the electricity mix is composed of mainly natural gas, solar and wind. The tendency that people buy smaller cars under scrappage programs is also important for realising the dual goal of GHG and NO_x emission reductions, as smaller vehicles cause less emissions due to fuel combustion and supply as well as vehicle production and the rebound effect is less prominent.

7 Appendix A

7.1 Matching HBEFA, KBA and PSI vehicle size classes

HBEFA operates with three size classes: <1.4L, 1.4-<2L and >2L. The size classes are matched to the German size classes as shown in Table 9.

Table 9 Size classes assignment

	German size classes	HBEFA	Aggregated size classes
SUV	Gelaendewagen	>= 2 L	Large
Van	Grossraum-Van	1,4-<2 L	Medium
Small	Kleinwagen	<1,4 L	Small
Lower medium	Kompaktklasse	<1,4 L	Small
Mini	Mini	<1,4 L	Small
Van	Mini-Van	1,4-<2 L	Medium
Medium	Mittelklasse	1,4-<2 L	Medium
Large	Obere Mittelklasse	>= 2 L	Large
Large	Oberklasse	>= 2 L	Large
SUV	Sportwagen	>= 2 L	Large
Van	Utilities	1,4-<2 L	Medium
Van	Wohnmobile	1,4-<2 L	Medium

7.2 Legislation years

Table 10 Legislation introduction years.

	Petrol	Diesel
Pre euro 0	< 1990	
Euro 0	1990-1991	
Euro 1	1992-1996	
Euro 2	1997-2000	
Euro 3	2001-2004	
Euro 4	2005-2009	
Euro 5	2010-2011	2010-2013
Euro 6	2011-	2014-

7.3 Natural lifetime and years remaining

As done by Knittel (2010), the expected lifetime conditional on surviving a certain time period is calculated from the survival probabilities (assuming independence of hazard rates across years). This serves as a proxy for the years remaining before the vehicle is naturally disposed of.

The survival curves are expressed by the Weibull distribution function [52]:

$$R(y) \;=\; exp\left[-\{y/y_{avg}\}\times\{\Gamma(1+1/b)\}^{b}\right]$$

Where

y is years, y_{avg} average lifetime and b shape parameter. Γ is the gamma function. Parameters used for calculation are shown in Table 11.

The conditional survival function can be used to calculate the survival probabilities given that a vehicle survives until year a and is expressed as [32]:

$$P(\text{vehicle survives a further time y}|\text{vehicle survives to a}) = R(y|a) = \frac{R(a+y)}{R(a)}$$

Where y is years and a is vehicle age.

The future expected lifetime of a vehicle at age a is the area below the conditional survival function $R(y|a)$.

A study by Oguchi and Fuse (2015) presents survival curves and average vehicle lifetime in Germany from 2000 to 2009. Additionally, vehicle stock data by cohorts [35] is used to confirm the survival curves. When not available directly in the vehicle stock data, new registrations in a specific year were obtained from [53]. By dividing the in-use vehicles of a specific cohort with the number of new registrations in the corresponding sales year a survival curve is obtained for each cohort. However, the data is not covering the full survival curve for each cohort, so an average survival curve is calculated. This implies that one cannot assess temporal variations in lifetime, but the vehicle lifetime in Germany is found to be fairly stable by Oguchi and Fuse (2015).

Using the vehicle stock data yields a slightly higher average lifetime than the estimates by Oguchi and Fuse (2015), which may be explained by the different data sources used and the fact that we have not accounted for the fact that sales occur during the whole year, while the number of in-use cars are just counted at the end of the year [52]. The parameters for the survival curves are shown in Table 11 and the values from Oguchi and Fuse (2015) are used for calculations.

Table 11 Parameters for survival curves used for calculations.

	Average lifetime, y_{avg}	**Shape parameter, b**
Vehicle stock data	14.2	2.6
Survival curve from Oguchi and Fuse (2015)[5]	14.1	2.9

8 Appendix B: Input data for 2009 program

8.1 Definition of emission concepts and emission factors

Pre Euro 0 and Euro 0 has no clear definition as emission categories. The emission factors from HBEFA used for these emission concepts are defined in Table 12.

No diesel particle filter (DPF) is assumed for emission concepts before Euro 4. Euro 4 cars are assumed to have a DPF in place (Ulrich Höpfner, personal communication 23.04).

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[5] Year 2006 parameters, as a year not influenced by the scrappage program should be used

Table 12 Assignment of emission concepts to euro classification.

Emission concept	Gasoline	Diesel
Pre Euro 0	ECE 15/03	PC diesel conv
Euro 0	Average of conv other concepts and Ucat	PC diesel 1986-1988
Euro 4		With diesel particle filter (DPF)

8.2 Characteristics of exchanged vehicles

8.2.1 Vehicle Size

The size classes are aggregated to align with the size classes of earlier studies at PSI, as presented in Table 9. The “Sonstige” cars were distributed according to the size distribution.

8.2.2 Euro class

The euro class is only known for new vehicles. The clunkers were assigned to euro classes by the known age distribution [38]. Knowing that the clunkers in 2009 were all older than 9 years old, they were either pre Euro 0, Euro 0, Euro 1, Euro 2 or potentially Euro 3. The Euro 3 cars were few (Koch, N. personal communication, Jan 2019) so for simplicity it is assumed that the clunkers were Euro 2 or earlier emission concepts. The relation between age and emission concept is based on the introduction years (Table 10) and is displayed in Table 13. In reality the emission concepts may be overlapping as vehicles with a given emission standard may become available before the emission standard is enforced.

Table 13 Assignment of euro classes to vehicle age

Age	Emission concept
> 18 years	Pre Euro 0
17-18 years	Euro 0
13-16 years	Euro 1
9-12 years	Euro 2

8.2.3 Diesel share

No statistics are available for the diesel share of the exchanged cars under the program (*Höpfner, U., personal communication, march 2019).* Through personal communication with IFEU the diesel share of scrapped cars is indicated to represent about 14% of the mileage of the scrapped cars. Using the vehicle stock data from 2009 [39] and 2010 [40] the stock change (which is assumed to represent scrapped vehicles) per euro class and engine type can be determined. This yields an average diesel share of 11.5% for the emission concepts before euro 3. This corresponds to a diesel share of about 16% if the mileage is depending on age, powertrain and size as described in the average statistics. The diesel share of the new vehicles is assumed to equal 7.5%, as estimated by IFEU [24].

The diesel share of old cars is also differentiated by euro class by using the vehicle stock data from 2009 and 2010. As the diesel share of the new vehicles bought under the program is lower than for the average new registrations in 2009 [39], these are adjusted to yield an average diesel share of 7.5% for the cars in the program.

Table 14 Diesel shares by euro class. The first row contains the shares from the vehicle stock data. The second row shows the diesel shares used in the study and is adjusted to yield the known average diesel shares of vehicles in the program. Data from: [39]

	pre euro 0	euro 0	euro 1	Euro 2	euro 4	euro 5	euro 6
Stock data	16,91 %	16,91 %	6,28 %	15,08 %	17,22 %	42,23 %	99,97 %[6]
Adjusted	16,91 %	16,91 %	6,28 %	15,08 %	6,03 %	14,78 %	34,99 %

8.2.4 Annual kilometres driven

8.2.4.1 Annual kilometres depending on age, size and powertrain

For the second scenario, annual kilometres driven is assumed to depend on size, powertrain and vehicle age [25]. A publication from 2014 [54] provides information on annual kilometres related to vehicle age and powertrain for private vehicles. A report on German mobility from 2008 [55] presents average annual kilometres driven for different vehicle size classes. The assumption that this figure is representative both for petrol and diesel cars had to be made, as only average figures were available. Combining these data sources yields an estimate for annual kilometres driven by size, powertrain and emission concept as displayed in Figure 17.

The difference in annual mileage for diesel and gasoline cars is significant. A new diesel car is driven twice as many kilometres as a new gasoline car. The decrease in annual mileage with vehicle age is more significant for diesel cars than for gasoline cars.

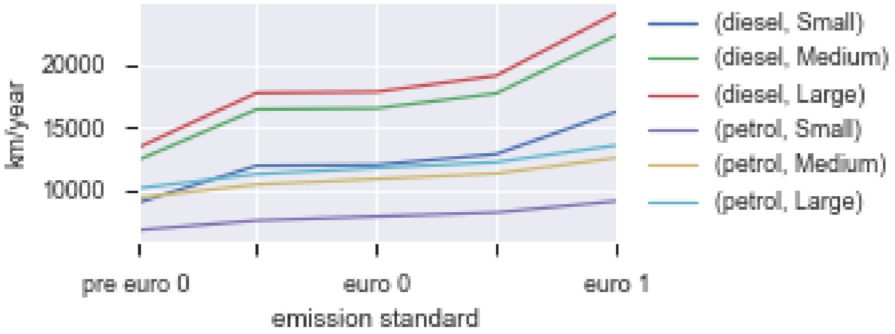

Figure 17 Annual kilometres driven in Germany by powertrain, size class and vehicle age.

8.2.4.2 Rebound effect

A 10-15% rebound effect is used [27]. The fuel economy improved by about 10% from the older euro concepts (pre euro 0-euro 2) to euro 4, leading to an increased driving of about 1.5% for the new cars.

8.2.5 Years remaining before “natural” scrappage

As described earlier, the lifetime reduction is determined from the survival curves. The years used are shown in Table 15.

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[6] Very few euro 6 cars were purchased in 2009, as the emission standard was not introduced yet – therefore the large share of diesel.

Table 15 Calculated expected remaining lifetime in years of the clunkers of a specific emission concept/age.

	Euro 2	Euro 1	Euro 0	Pre Euro 0	Average
Average age of emission concept	11 years	14.3 years	17.4 years	20.6 years	
Average years remaining	5.12	3.77	2.88	2.22	3.98

9 Appendix C: Input data for hypothetical BEV program

The number of vehicles eligible for a program limited to diesel cars with an emission standard of euro 5 or earlier was determined from the vehicle stock data available from KBA [42]. Considering the 59 cities where NO_2 limits are exceeded and data available on county level [41], about 2.6 million diesel vehicles have an emission standard of euro 5 or older. The program considers replacing the 2 million oldest ones.

9.1 Characteristics of exchanged vehicles

9.1.1 Vehicle Size

The size of old vehicles is determined by vehicle stock data, which is available by motor displacement volume on county level. The motor displacement volume is taken as a proxy for the vehicle size. Small vehicles refer to engine displacement <1.4 L, medium to 1.4-<2L and large to >= 2L.

The size distribution of the new BEVs are assumed to equal the distribution of the other BEVs bought under the current subsidy scheme for BEV in Germany [43]. Additionally, the number of new registrations in 2018 of larger BEVS (such as Tesla) is added. Using the data for the number of vehicles bought and the corresponding model a size distribution is generated using the size classification in Table 9. The size distribution of new BEVs are assumed to be the same in all counties.

9.1.2 Euro class

The euro class of the old cars in each county is directly available from KBA data [42].

9.1.3 Years remaining before “natural disposal”

The same procedure as for the 2009 program is used to estimate the years remaining of the vehicles traded in. The average age of each euro class is calculated assuming that the program is introduced in 2020 and using the legislation introduction year. The estimated years remaining are shown in Table 16.

Table 16 Expected years remaining for each emission concept.

	Euro 5	Euro 4	Euro 3	Euro 2	Euro 1
Average age	8 years	12.5 years	17.5 years	22 years	25.5 years
Average years remaining	7.33	5.00	3.50	2.46	1.97

9.2 Electricity mixes

The current average German electricity mix is updated with data from 2018 [56]. This electricity mix is fossil-fuel dependent: 38% coal and 13% natural gas. Solar and wind have market shares of about 12% each.

The German marginal electricity mix is taken from ecoinvent 3.5 consequential long-term [45] and is composed of 51% wind, 33% solar and 13% natural gas.

10 Appendix D: Future program

10.1.1 Stock projection

To predict the 2030 stock, vehicle stock data in each county [42] is used together with the vehicle survival curve. The conditional survival curve is calculated for each euro class knowing the average age. The probability that the car is still in the stock in 10 years is then determined, which is used to estimate the cars of a specific euro class leaving the stock before 2030.

All cars leaving the stock are assumed to be replaced by a euro 6d diesel vehicle. Emission factors for euro 6 cars from HBEFA 3.3, with reference year 2015 are used for the euro 6 vehicles replaced that are already in the stock today. 261’567 euro 6 cars replaced will be purchased in the period between 2020 and 2030. Emission factors for these cars correspond to euro 6d-2 and are taken from HBEFA 3.3 with reference year 2020.

10.1.2 Years remaining before “natural” disposal

The years remaining before natural disposal are estimated as described earlier and shown in Table 17.

For euro 6 cars the legislation introduction year of the earliest euro 6 standard was 2014. 1’524’637 euro 6 cars in the 2020 stock are replaced in 2030. These cars are assumed to be 3 years old on average in 2020 and thereby 13 years in 2030. 261’567 of the euro 6 cars replaced will be purchased between 2020 and 2030, and are assumed to have an average age of 5 years in 2030.

Table 17 Expected remaining lifetime for each emission concept.

	Euro 6 d	**Euro 6**	**Euro 5**	**Euro 4**	**Euro 3**	**Euro 2**	**Euro 1**
Current average age (2020)		3 years	8 years	13 years	17.5 years	21.5 years	29.5 years
Average age 2030	5	13	18	23	27.5	31.5	
Average years remaining	9.47	4.80	3.25	2.38	1.75	1.38	

10.1.3 Electricity mixes

The electricity markets in ecoinvent 3.5 cut-off are modified by using scenarios from the integrated assessment model REMIND. This yields the average electricity mixes for 2030. Additionally the German marginal electricity mix is calculated using the electricity mixes in 2030 and 2040. As the results from REMIND only covers Europe as a region, GDP shares are used to determine the electricity generation in Germany in 2030 and 2040.

11 Supplementary results

11.1.1 Link to maps

11.1.1.1 Marginal electricity mixes

Reduced impact from decreased direct emissions https://datawrapper.dwcdn.net/Efw06/4/

Reduced impact from decreased direct emissions per car https://datawrapper.dwcdn.net/yqklJ/4/

Impact when allocating indirect emissions to counties https://datawrapper.dwcdn.net/aRdRk/6/

Impact when allocating indirect emissions to counties per car https://datawrapper.dwcdn.net/w4046/3/

11.1.1.2 Average electricity mixes

Health impact from decrease in direct emissions: https://datawrapper.dwcdn.net/DFBr1/1/

Health impact per car from decrease in direct emissions: https://datawrapper.dwcdn.net/AnSOx/1/

Impact when allocating indirect emissions to counties https://datawrapper.dwcdn.net/nw2L2/3/

Impact when allocating indirect emissions to counties per car https://datawrapper.dwcdn.net/4IC3k/2/

Table 18 Air pollutant emissions in future and current BEV program. Negative values indicate savings, all values in Mt.

		PM2.5	PM10	NOx	SO2	NH3	NMVOC
Future program	Direct emissions	-0.000219	0.00004	-0.06	-0.000083	-0.000141	-0.000926
	Indirect emissions	0.0045	0.0064	0.0088	0.04	0.002	0.0073
	Life-cycle emissions	0.0043	0.0064	-0.053	0.04	0.0019	0.006
Current program	Direct emissions	-0.0012	0	-0.12	-0.000103	-0.000152	-0.00147
	Indirect emissions	0.015	0.0094	0.027	0.07	0.0012	0.0086
	Life-cycle emissions	0.014	0.0094	-0.093	0.07	0.00105	0.007

11.1.2 Emission factors air pollutants

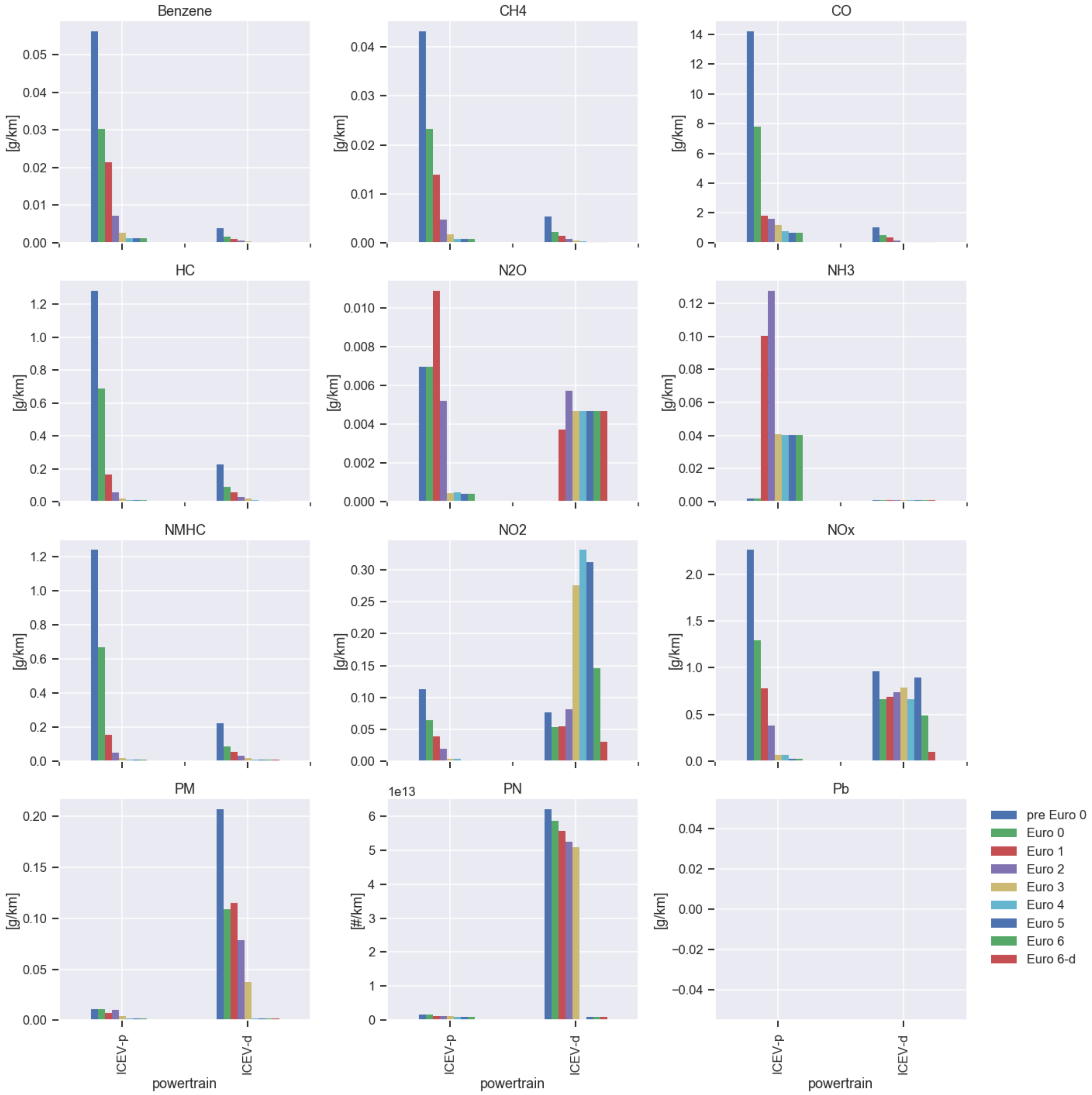

Figure 18 Tailpipe emission factors for air pollutants of passengers with different Euro emission standards.

11.1.3 Emission factors fuel related

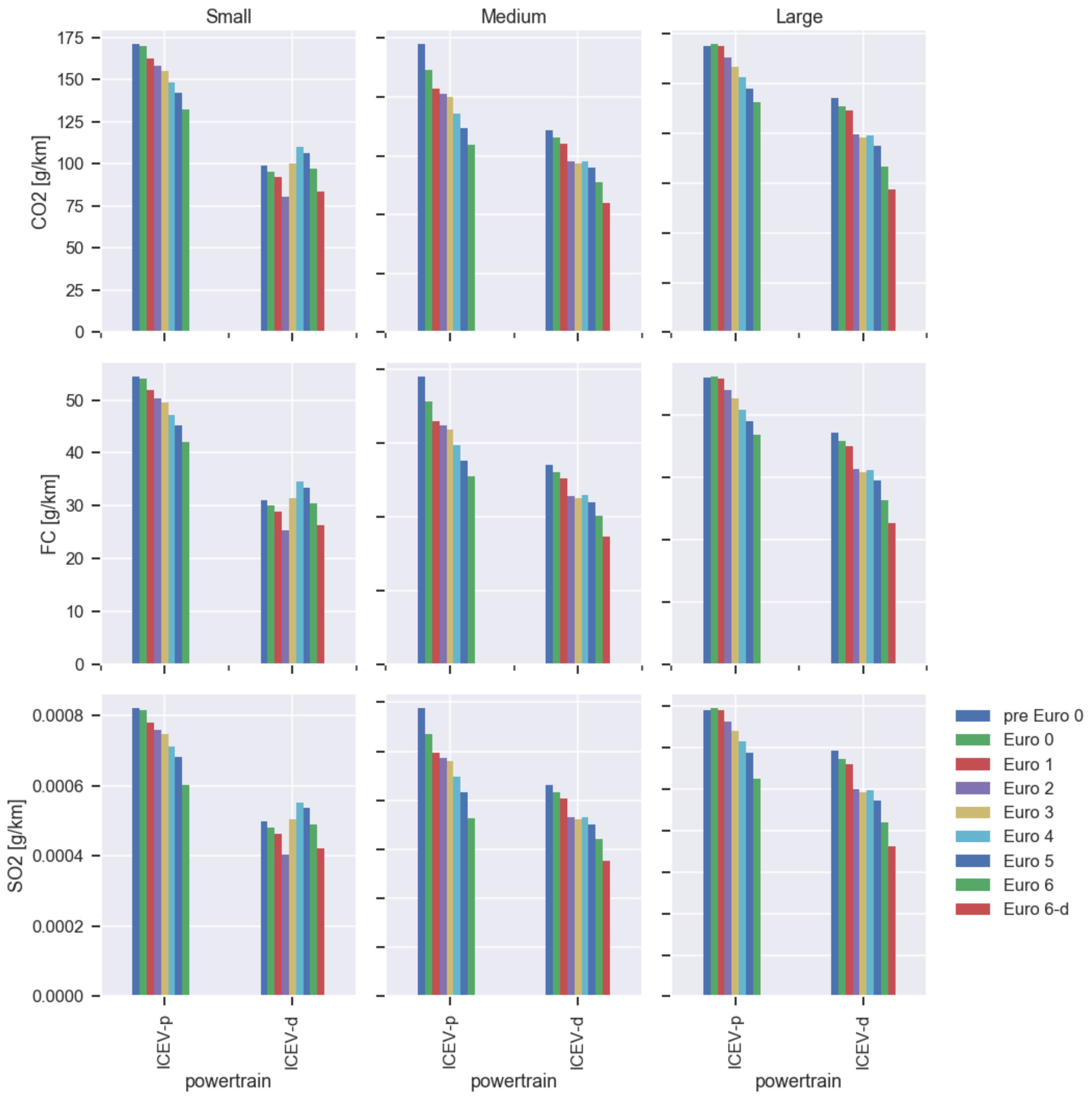

Figure 19 Tailpipe emission factors for CO2 and SO2 and fuel consumption (FC) of passengers with different Euro emission standards.

11.1.4 LCA results

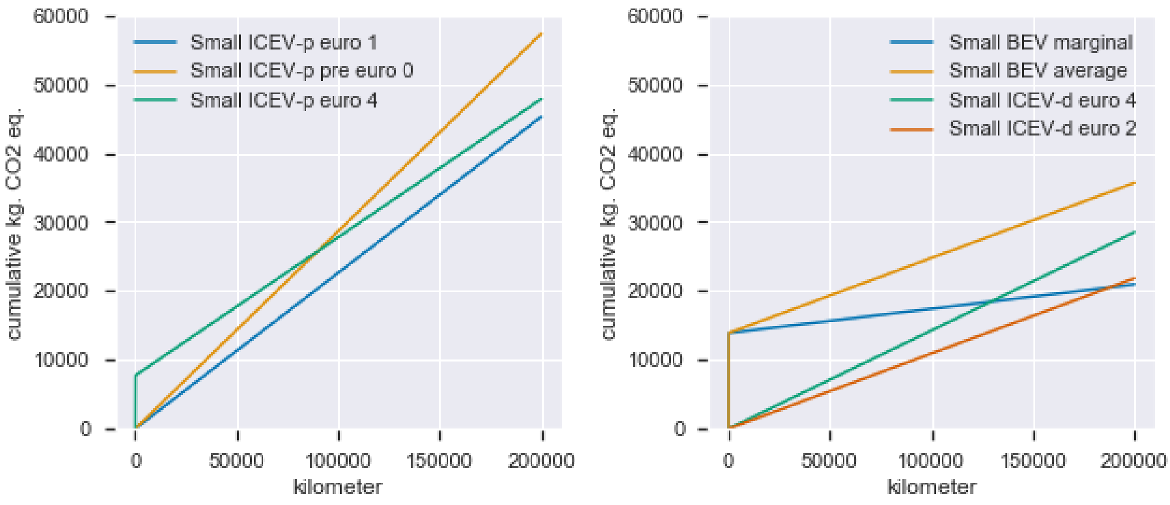

Figure 20 Climate change impacts

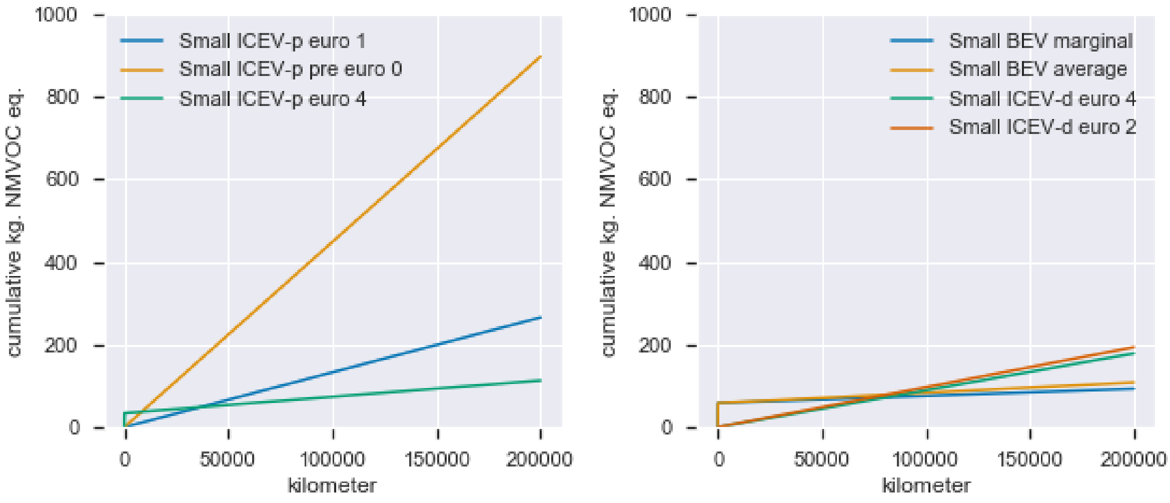

Figure 21 Photochemical oxidant formation

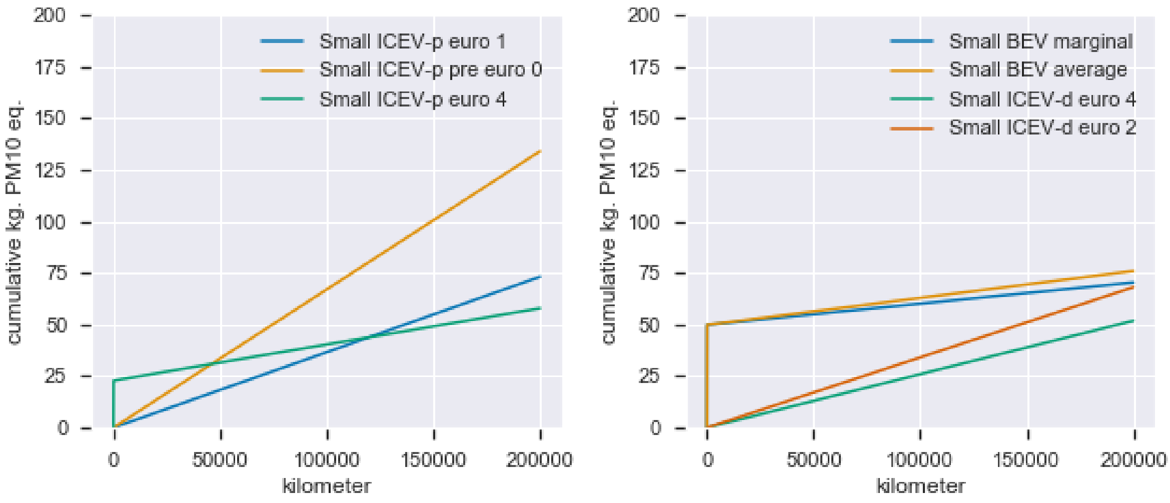

Figure 22 Particulate matter formation

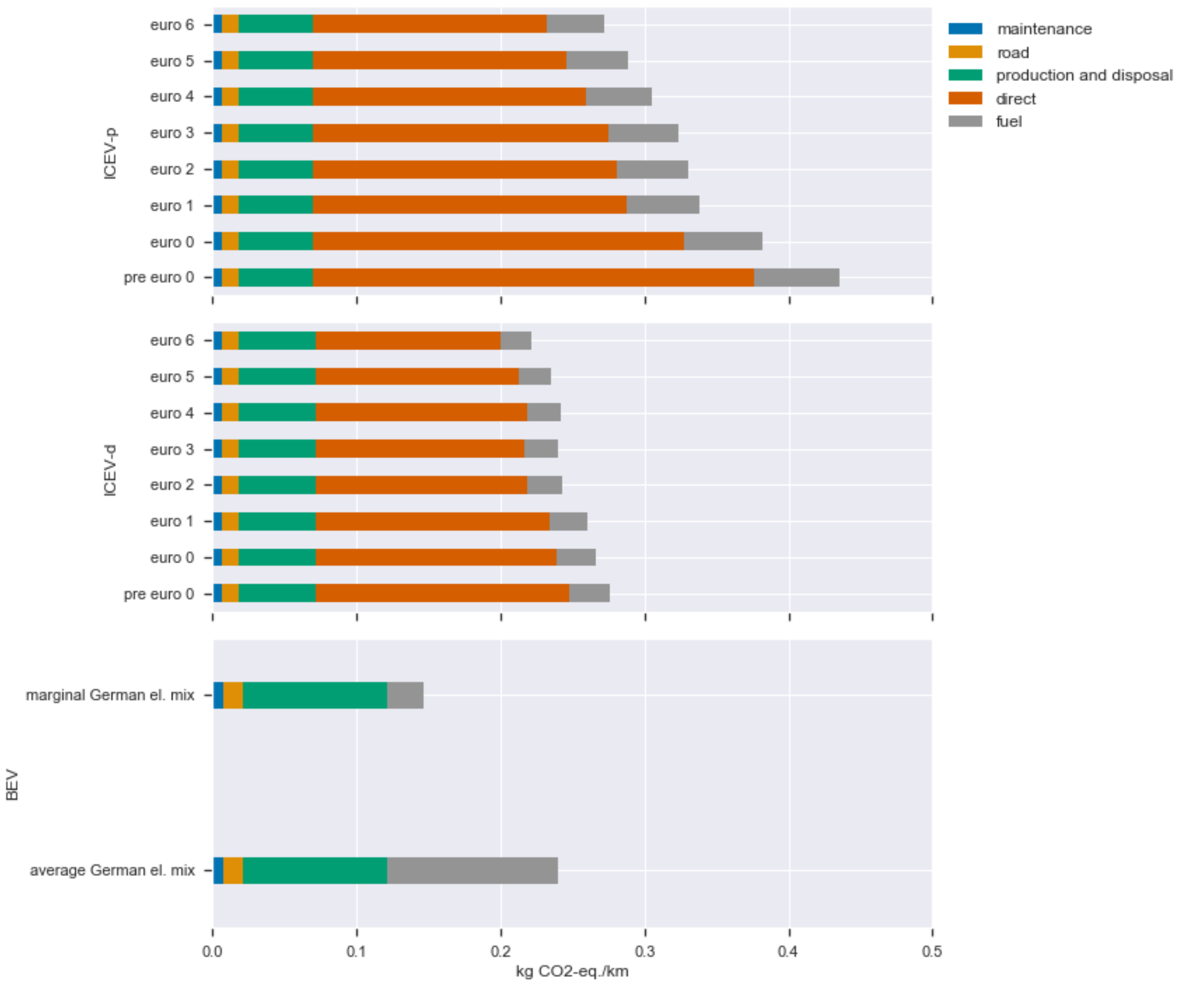

Figure 23 Climate change impacts

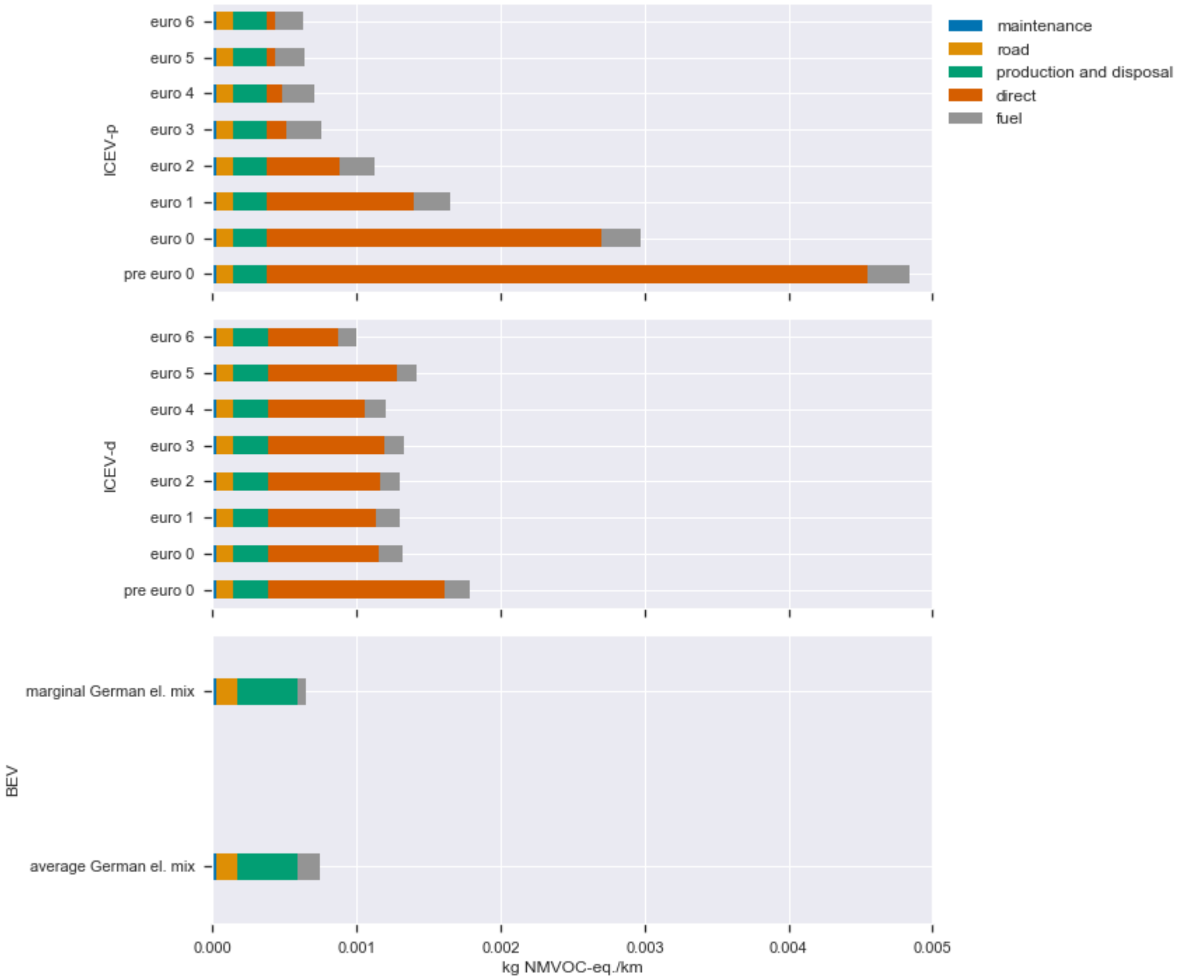

Figure 24 Photochemical oxidant formation impacts

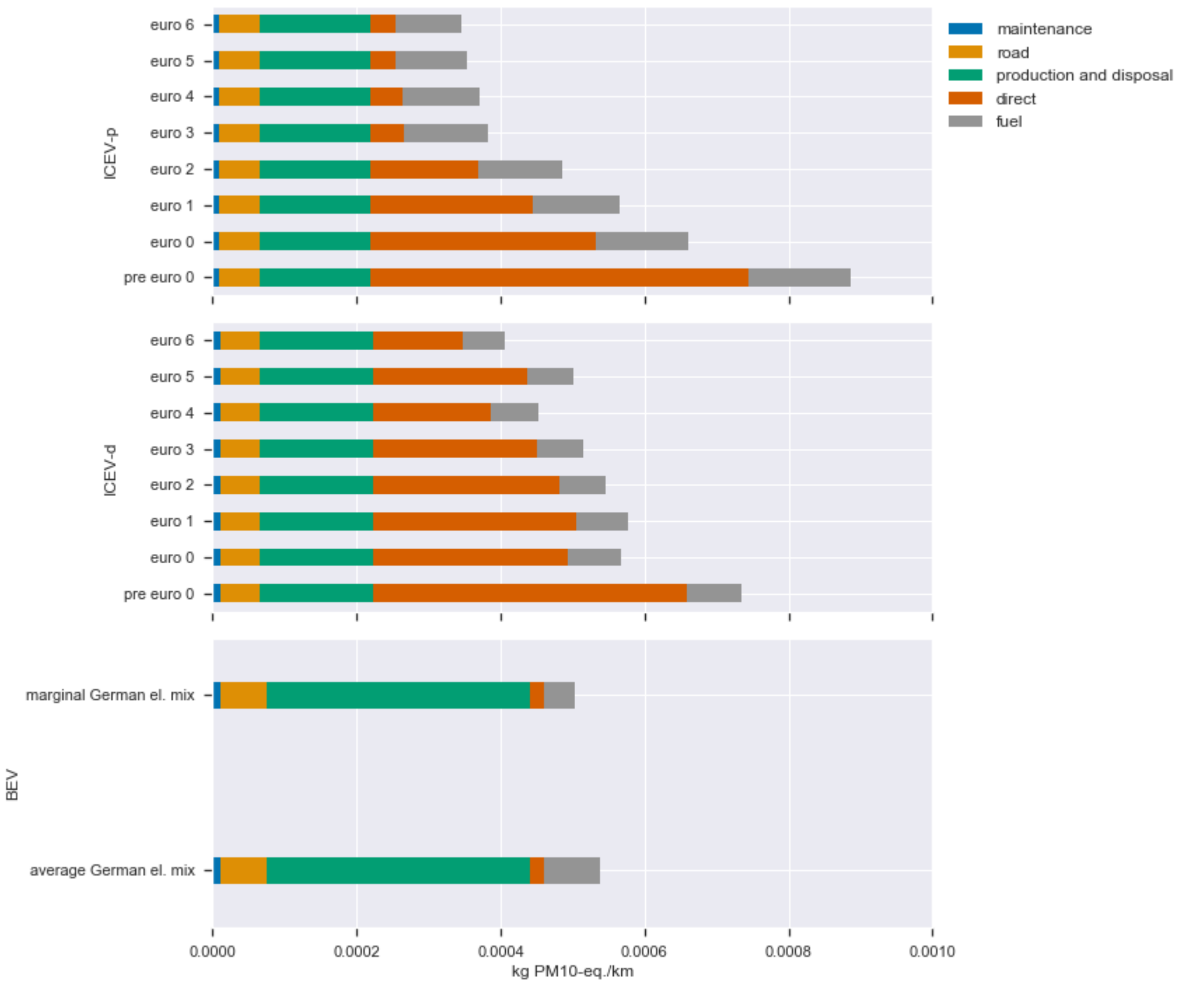

Figure 25 Particulate matter formation

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