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CO_2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European "diesel boom"

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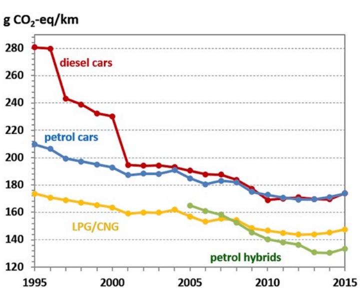
GRAPHICAL ABSTRACT



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ABSTRACT

A comprehensive overview is provided evaluating direct real-world CO_2 emissions of both diesel and petrol cars newly registered in Europe between 1995 and 2015. Before 2011, European diesel cars emitted less CO_2 per kilometre than petrol cars, but since then there is no appreciable difference in per-km CO_2 emissions between diesel and petrol cars. Real-world CO_2 emissions of diesel cars have not declined appreciably since 2001, while the CO_2 emissions of petrol cars have been stagnant since 2012. When adding black carbon related CO_2-equivalents, such as from diesel cars without particulate filters, diesel cars were discovered to have had much higher climate relevant emissions until the year 2001 when compared to petrol cars. From 2001 to 2015 CO_2-equivalent emissions from new diesel cars and petrol cars were hardly distinguishable. Lifetime use phase CO_2-equivalent emissions of all European passenger vehicles were modelled for 1995–2015 based on three scenarios: the historic case, another scenario freezing percentages of diesel cars at the low levels from the early 1990s (thus avoiding the observed "boom" in new diesel registrations), and an advanced mitigation scenario based on high proportions of petrol hybrid cars and cars burning gaseous fuels. The difference in CO_2-equivalent emissions between the historical case and the scenario avoiding the diesel car boom is only 0.4%. The advanced mitigation scenario would have been able to achieve a 3.4% reduction in total CO_2-equivalent emissions over the same time frame. The European diesel car boom appears to have been ineffective at reducing climate-warming emissions from the European transport sector.

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1. Introduction

Climate change is widely accepted as being the biggest environmental challenge worldwide so far (e.g. Rockström et al., 2016). It has been addressed in international protocols initiated in Kyoto in 1997 followed by several amendments, recently in Paris in 2015 (UNFCCC, 2015). The transport sector contributed 24% of the worldwide CO_2 emissions in 2006; 70% of these emissions were from road transport alone (Schipper et al., 2011). In the European Union (EU), road transport in 2012 contributed 82% of the total transport-related final energy use, with passenger cars contributing 60% of this share (Motowidlak, 2016). More importantly, transport has shown the most rapid growth in energy consumption of all sectors (Motowidlak, 2016).

The EU's climate change mitigation efforts for road transport have focussed on reducing the average CO_2 emissions of newly registered cars (e.g., EEA, 2017). These emission values are measured using standardized driving cycles such as the New European Driving Cycle (NEDC), which is conducted under idealized laboratory conditions, and not representative of real-world driving conditions.

On-cycle measurements, however, today differ very much from emissions under real-world driving conditions. The non-governmental organisation International Council on Clean Transportation (ICCT) evaluated around one million points of real-world fuel consumption data (Tietge et al., 2016), for the first time offering an approximation of real-world fuel consumption and CO_2 emission values of passenger cars. In recent years, the gap between on-cycle and real-world emissions has been growing, reaching an average deviation of +42% for new passenger cars in 2015 in Europe (Tietge et al., 2016).

European Union and member states institutions quantify greenhouse gas (GHG) emissions in accordance with the United Nations Framework Convention on Climate Change, namely the “Kyoto protocol” and subsequent amendments (see UNFCCC, 2015). The European Environmental Agency (EEA), for example, considers just CO_2, CH_4, and N_2O emissions when quantifying the carbon footprint of diesel and gasoline fuel used for road transport (EEA, 2012).

Direct emissions of other greenhouse gases (CH_4 and N_2O) by passenger vehicles is in the range of 1–2% of the GHG emissions (Defra, 2012; CDP, 2016) as expressed in CO_2-equivalents. The amount of CH_4 and N_2O emissions relative to the total well-to-wheel GHG emissions is 1.5% in case of diesel fuel and 1.7% in case of petrol (Fritsche, 2007).

Based on the motivation to save CO_2 emissions, in the two decades since 1995, Europe faced a massive technology change from the petrol driven passenger car to the diesel car (reviewed in Cames and Helmers, 2013).

In the early 1990s, diesel shares of new car registrations and the European fleet was around 10–15% (Cames and Helmers, 2013).

From 1990 to 2014, the diesel share of the European fleet grew from 11% (Cames and Helmers 2013), to 41% (ACEA, 2016). In 2014, there were 253 million cars in use in the EU(28) (ACEA, 2016). 41%, or 104 million of these cars were diesel powered. About 281 million cars were newly registered in the EU-15 between 1995 and 2015 (ACEA, 2016), among them 122 million diesel cars and 159 million petrol cars (calculated from ACEA, 2016; cars propelled by LPG [liquefied petroleum gas] and NG [natural gas] cars neglected). Without political support for the diesel car over the past 20 years, and assuming diesel as well as petrol cars would have remained stable in terms of market shares from 1995 (22.6% and 77.4%, respectively), about 58 million cars would have been petrol powered instead of diesel powered between 1995 and 2015 in the EU-15.

Passenger vehicles are also a significant source of air pollutants such as NO_x (oxides of nitrogen) and PM (particulate matter), which leads to high rates of premature mortality in the EU (EEA, 2016a; Anenberg et al., 2017).

One component of the PM emitted by passenger vehicles is Black Carbon (BC), which is an especially large fraction of the PM emitted by diesel engines (for details see Tables 1 and 2). BC exerts a net positive radiative forcing of the climate system by absorbing solar radiation while suspended in the atmosphere, and after being deposited to snow and ice surfaces. BC can also alter the properties and lifetimes of cloud droplets and ice particles, producing indirect radiative forcing of varying sign and magnitude. Using a comprehensive set of observations and modelling studies, Bond et al. (2013) quantified the warming effects of BC, and calculated a total radiative forcing due to BC in the industrial era of 1.1 Wm^{-2}, within 90% uncertainty bounds of 0.17–2.1 Wm^{-2}, making BC the second most important anthropogenically emitted substance in terms of its climate impact. The large uncertainty range is due to both measurement error and limitations in present understanding of many of the key processes involved in the radiative forcing of BC. As a component of PM, BC is subject to several removal processes which do not affect CO_2, for example dry deposition to surfaces and washout by rain droplets. The atmospheric lifetime of BC is thus of the order of days to weeks. Bond et al. (2013) also calculate Global Warming Potentials (GWP, expressed as carbon dioxide equivalent, or CO_2-eq) for BC. Due to the difference in lifetime between BC and CO_2, the GWP of BC is highly dependent on the integration timescale, with shorter timescales leading to higher GWP values for BC. Bond et al. (2013) calculated the GWP20 (time horizon 20 years) of BC to be 3200 (270–6200), and the GWP100 (time horizon 100 years) to be 900 (100–1700). The uncertainty ranges are due to the uncertainty in the radiative forcing of both BC and CO_2.

BC is excluded by European Union and EU member states institutions when it comes to quantification and reporting of radiative forcing species. The reason is that the Kyoto protocol focuses exclusively on greenhouse gases. Although being recommended since a long time (e.g. Bond and Sun, 2005), it was not until the Paris Agreement in 2015 when BC was addressed on a voluntary basis by a few nations in their Intended Nationally Determined Contributions (INDCs). However, reporting of BC emissions is now encouraged under the Convention on Long-range Transboundary Air Pollution since the 2012 amendment of the Gothenburg Protocol. The amended protocol is the first international treaty specifically including black carbon as a short-lived climate forcing pollutant (SLCP; EEA, 2013). Reducing emissions of BC and other SLCPs would have the advantage of simultaneously decreasing the future global warming as well as significantly improving worldwide health (UNEP, 2011; Shindell et al., 2012). European countries have

Table 1
Annual Fuel Consumption (FC) values assumed for new registered vehicles of different Euro class (of corresponding year) and different fuel types (calculation from real-world CO_2 emissions in Fig. 1C as described in text).

year	Euro class	FC real-world (MJ/km)				
		Diesel	Petrol	P. hybrid	LPG	CNG
1995	Euro 1	2.63	2.82		2.67	3.04
1996	Euro 1	2.61	2.77		2.63	2.99
1997	Euro 2	2.57	2.74		2.60	2.96
1998	Euro 2	2.51	2.71		2.57	2.92
1999	Euro 2	2.42	2.68		2.54	2.89
2000	Euro 2	2.39	2.66		2.52	2.86
2001	Euro 3	2.29	2.58		2.45	2.78
2002	Euro 3	2.31	2.60		2.46	2.79
2003	Euro 3	2.34	2.59		2.46	2.79
2004	Euro 3	2.35	2.63		2.49	2.83
2005	Euro 3	2.34	2.55	2.28	2.42	2.74
2006	Euro 4	2.35	2.49	2.22	2.36	2.68
2007	Euro 4	2.37	2.52	2.18	2.39	2.72
2008	Euro 4	2.35	2.51	2.11	2.38	2.70
2009	Euro 4	2.29	2.41	2.01	2.29	2.60
2010	Euro 5	2.26	2.38	1.94	2.26	2.56
2011	Euro 5	2.28	2.35	1.91	2.23	2.53
2012	Euro 5	2.29	2.33	1.88	2.21	2.51
2013	Euro 5	2.27	2.34	1.81	2.21	2.52
2014	Euro 5	2.27	2.36	1.80	2.23	2.54
2015	Euro 5	2.33	2.40	1.84	2.27	2.58

Table 2
Type approval and real-world PM emission factors and corresponding fractions of BC (fBC) in PM emissions for vehicles of different Euro classes and different fuel types. PM real-world EF were assumed in the emission modelling and BC fractions applied afterwards to determine yearly BC emissions.

Fuel type	Euro Standard	PM limit - type approval [a] (mg/km)	PM real-world (mg/km)[b]	BC/PM[c] (fBC)
Petrol	Euro 1	–	25	0.25
	Euro 2	–	3	0.25
	Euro 3	–	3	0.15
	Euro 4	–	3	0.15
	Euro 5	5	3	0.15
Diesel	Euro 1	140	136	0.7
	Euro 2	90	73	0.8
	Euro 3	50	34.8	0.85
	Euro 4	25	31.8	0.87
	Euro 5	5	5.1	0.2
P. Hybrid	Euro 4	–	0.4	0.125
	Euro 5	5	0.4	0.125
LPG Bifuel	Euro 1	–	1.2	0.117
	Euro 2	–	1.2	0.117
	Euro 3	–	1.2	0.117
	Euro 4	–	1.2	0.117
	Euro 5	5	1.2	0.117
CNG Bifuel	Euro 4	–	1.2	0.117
	Euro 5	5	1.2	0.117

Note: BC emissions for diesel vehicles dependent on DPF penetration rate per year (see Fig. 2), i.e., BC = PM * fBC (with DPF) *%DPF + PM * fBC (without DPF) *(100- %DPF) (e.g. BC 2001 = PM2001 * 0.2 * 10% + PM2001 * 0.85 * 90%.

[a] PM type approval data taken from Dieselnet.com (2017).

[b] Average values considered from different sources: Tate 2013, 2015 – PM real-world Emission for Diesel Euro 1 to 4: 30, 34, 21, 11, respectively. Kadijk et al., 2015 – PM real-world Emission for Diesel Euro 1 to 4: 240, 110, 30, 35, respectively. Hooftman et al., 2016 – PM real-world Emission for Diesel Euro 4 and Euro 5 (with DPF): 50, 1.1–2.8, and Petrol Euro 4–6: 1.5–2.4, respectively. Pillot et al., 2014 – PM real-world Emission for Diesel Euro 4: 35. Shields, 2016 - PM real-world Emission for Petrol Hybrid: 0.06–0.7 (here assumed for Euro 4 and 5). Ligterink, 2017 (Averages calculated from urban, rural, and highway driving) – PM real-world Emission (factors) for Diesel all Euro classes: 139, 83, 36, 28, 8.3 and for Petrol Euro 1 and remaining classes: 25 and 4.0. Vouitsis et al., 2017 – PM real-world Emission (factors) for Diesel Euro 2 and 3: 65 and 52; and for LPG: 0.7 and CNG: 1.6. Numbers from standardized driving cycles neglected to remove possible cheating.

[c] EEA (2018), Table 3–91, fBC for Petrol Euro 5 assumed the same as for Euro 4, and for Diesel Euro 5 assumed the average between 0.1 of "equipped with DPF and fuel additive" and 0.2 of "equipped with a catalyzed DPF".

decided to do the opposite in the past 20 years by promoting diesel car sales: Many diesel cars as marketed in Europe in the past 20 years have much higher BC emissions (see below) as well as up to 15 times higher NO_x emissions as per g NO_x/kg fuel consumption according to real-world measurements (Chen and Borken-Kleefeld, 2014) in the direct comparison with petrol cars.

Jacobson et al. (2004; Jacobson, 2005) modelled a theoretical conversion of the entire US car fleet from petrol to diesel, and based calculations on the strictest applicable EU emissions thresholds (Euro 5/6) of European-type passenger cars. They investigated the effects of these emissions (including BC, NO_x, and VOC (Volatile Organic Compounds), which together with NO_x are precursors for ground-level ozone), and concluded (1) that enhanced NO_x emissions in combination with a changed NO_2:NO ratio would "drive up photochemical smog, including total column ozone" (Jacobson et al., 2004), and (2) "diesel cars … may warm climate per distance driven over the next 100 + years more than equivalent gasoline cars" (Jacobson, 2005). In Europe, research on the impact of elevated NO_x emissions as emitted from diesel cars is in the early stages, indicating an increase of ozone Europeanwide caused by excess NO_x emissions (Jonson et al., 2017), however with distinct regional differences (von Schneidemesser et al., 2017).

Japan removed diesel cars from the market after 1995 because of the threat of particulate emissions towards human health (Cames and Helmers, 2013). In Europe, however, diesel cars without diesel particulate filters (DPFs) entered the fleet until the year 2010. In the year 2000, the Peugeot 605 was the first passenger car voluntarily equipped with a DPF (Böck, 2006). Even in 2010, there were just a few diesel vehicles with "open" DPFs, which have limited filtration capacity compared to "closed" systems (Helmers, 2010). There are no official statistics about the number of vehicles manufactured with DPFs because the European Commission "does not prescribe the technology to be used by car manufacturers to meet the limits" (EU, 2016). Implementation of Euro 5b-thresholds in September 2011 made DPF technically mandatory (Myung and Park, 2012), although their installation is not specified specifically. Accordingly, we assume the equipment of diesel cars with DPF rose linearly between 2000 and 2010 reaching 100% coverage around 2010. Older diesel cars without DPF are still allowed to be driven without restriction outside of Low Emission Zones.

2. Motivation and methods

Firstly, this paper investigates the real-world time trend of CO_2 emissions from passenger cars in Europe in the period from 1995 to 2015, which we refer to as the European "diesel boom". For the first time, we use real-world emission factors based on Tietge et al. (2017) to calculate the balance of real-world CO_2 emissions of passenger cars differentiated by diesel and petrol engines during this period. We are aware that it can be difficult to directly compare CO_2 emissions from diesel and petrol cars: In 2013, the average new diesel passenger car was 26% heavier, 21% more powerful, and had 31% larger engine compared with an average new petrol car (EEA, 2014). Between 2000 and 2015, new passenger cars in Europe grew from an average of 1300 kg to an average of 1400 kg in mass, this additional 100 kg load causing an increase from 0.3 to 0.5 L/100 km in fuel consumption or 7.5–12.5 gCO_2/km in emission, respectively (Fontaras et al., 2017). In this context it is remarkable that while maximum engine power of petrol cars remained almost constant since 1990 among new registrations, it grew from 67 to 100 kW between 1995 and 2010 in diesel cars (Carslaw et al., 2013), also reflecting their size growth in this period. Knittel (2012) provided the most detailed investigation of the effects of light duty vehicles power and weight increase on fuel consumption in the USA, an analysis missing so far for the European market. Specifically in Europe, however, millions of consumers were attracted in the investigated period (1995–2015) to switch from petrol to diesel cars by the fuel consumption advantages of diesel cars and the lower price of diesel fuel in many European countries, the latter often caused by a lower taxation of diesel fuel (Ajanovic, 2011). While increasing size and weight of their new vehicles (Ajanovic and Haas, 2012), these consumers were able to keep their energy service prices per km driven constant. These developments led to a rebound effect causing a loss of about 50% of theoretical savings due to more km driven with diesel cars and a loss of about 25% of theoretical savings, respectively, by switching to bigger diesel cars (Ajanovic and Haas, 2014). Although this rebound effect has been described early (Schipper et al., 2002), some European states still currently retain tax subsidies for diesel fuel.

The differences in weight and power between diesel and petrol cars do not interfere with our comparative analysis of the emission performance of diesel and petrol cars, because we are not evaluating a particular technology against another here, but are questioning whether the specific European policy approach of promoting diesel car sales was efficient with respect to mitigating climate change. We address this by comparing vehicle lifetime emissions from the historic case, a low-diesel cars-scenario and a third scenario with an increased number of cars based on alternative CO_2-efficient fuels available in the period 1995–2015. Exploration of further alternative scenarios in which the sale of smaller, less powerful diesel cars may have been explicitly

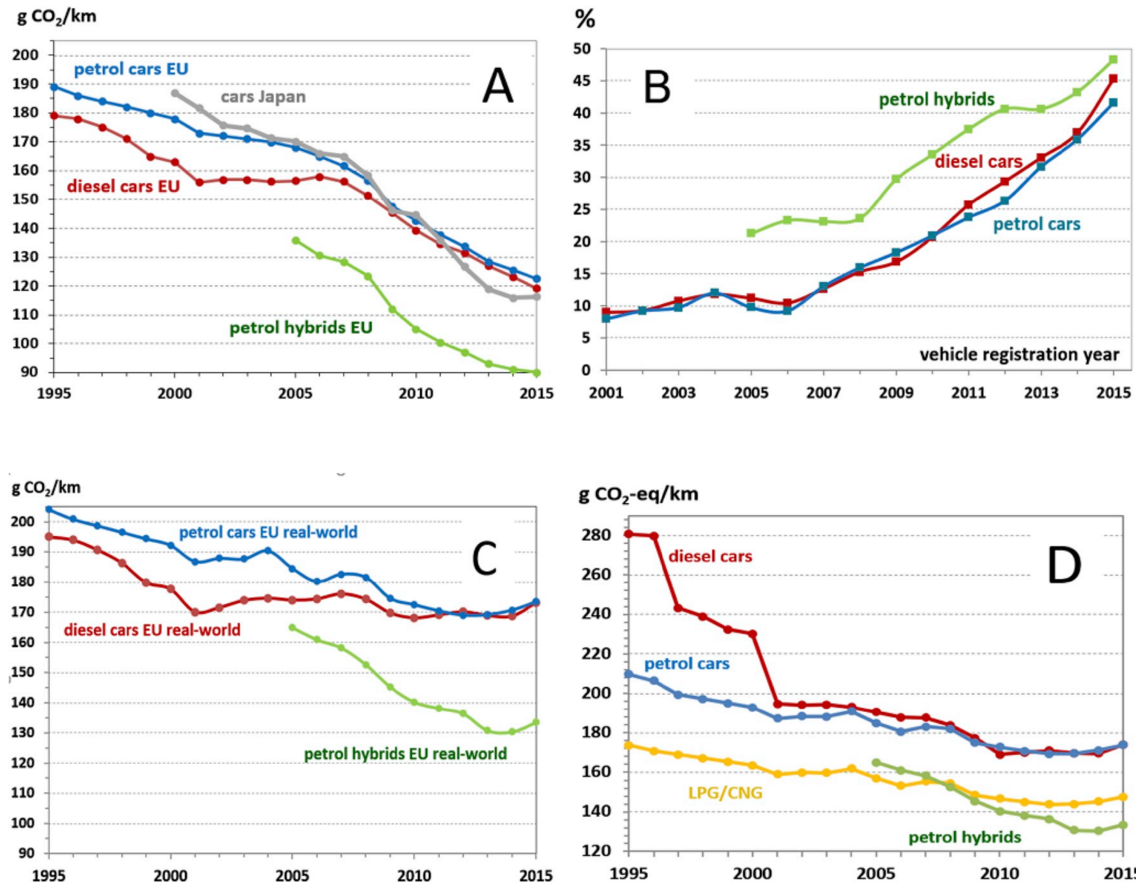

Fig. 1. A) Average type-approval CO_2-emissions of new cars in the EU and Japan. Sources: EU-15 Figures 1995 to 2003 (EU, 2005); recent EU Figures from EEA (2016b), the geographical scope of the data changing from EU-15 through EU-28. Japan data recalculated from JAMA (2015, 2016) and MLIT (2017). Japanese JC08 test cycle data converted to NEDC due to Kühlwein et al. (2014). Petrol hybrid cars: Data from ICCT (2016), number for 2005 extrapolated linearly; earlier data excluded because of high scattering due to small registration numbers. NEDC = New European driving cycle.
B) Divergence between type-approval and real-world CO_2-emissions for passenger cars in the EU (data source: Tietge et al., 2016). Divergence for hybrid passenger cars based on results obtained from Spritmonitor.de.
C) Average real-world CO_2-emission values of new cars in Europe. Calculation based on type-approval data (A) and divergence estimates as shown in (B) Petrol/diesel cars: Data for 1995–2000 calculated based on divergence estimates for the year 2001.
D) Total CO_2-eq emissions of new cars in Europe. Calculation based on the sum of real-world CO_2 emissions (C) and contribution of real-world BC emissions (based on values from Table 2 and GWP100 of 900).

encouraged, or in which larger, more powerful petrol vehicles may have been favoured over their diesel-powered equivalents is beyond the scope of the present study, and remains an interesting topic for future research.

In addition to direct CO_2 emissions, we consider the additional radiative forcing due to primary-emitted BC, in order to compare diesel and petrol vehicles in terms of CO_2- equivalent emissions (CO_2-eq). Other GHGs, like CH_4 and N_2O, were not considered due to their small contribution to tailpipe GHG emissions (see above). An investigation of the effects of the diesel boom on tropospheric ozone is beyond the scope of this study.

2.1. Real-world CO_2 emissions

Between 1999 and 2015, type approval CO_2 emissions of newly registered petrol cars in Europe decreased by 29.9%. In the same time, Japan was able to decrease CO_2 emissions by 37.7% (Fig. 1A). Japan went a different route than Europe: 17% of all 2014 passenger car sales in Japan were petrol hybrid cars, while just 1.8% were diesel powered (JAMA, 2016).

Fig. 1A shows the official CO_2 values of new diesel and petrol cars in the EU when measuring the performance of the car industry to reduce passenger car CO_2 emissions (e.g. EU, 2014). Real-world emissions, however, have been increasingly deviating from these values. Tietge et al. (2016) evaluated real-world fuel consumption data from seven European countries. Even though this dataset is based on individual driving styles and varying driving conditions, large samples of real-world fuel consumption values tend to cluster around central estimates (Tietge et al., 2016). Samples have been shown to be reasonably representative of new car fleets, though the possibility about self-selection bias affecting the level of measured fuel consumption values remains (Mock et al., 2013, Tietge et al., 2016, 2017).

From Tietge et al. (2016) only the six largest data sets were included in analysis. The remaining were excluded from our analysis due to their small sample size (< 3000) within the period of investigation. One dataset (Allstar fuel card) includes only diesel car data (242,353 vehicles). The datasets from Spritmonitor (DE), Travelcard (NL), Honestjohn (UK), Allstar fuel card (UK), Cleaner Car (NL), and Fiches auto (FR) with 23,559 to 275,764 entries (Tietge et al., 2016) were considered for data processing, altogether resulting in 784,124 entries. These data were processed here in a new way by calculating the average divergence between type-approval and real-world values for each year from 2001 to 2015, separated by petrol and diesel, based on the fleet of vehicles analysed by Tietge et al. (2017). The evaluation shown in Fig. 1B is based on 8786 entries (2001) to 98,251 entries (2012) per year for diesel and petrol cars together. The data were weighed by number of entries per data source by year. Different data sources furnish different levels of divergence, but the trend in all data sources is similar and aggregated results, as shown in Fig. 1B, present a clear upward trend in all powertrains. For example, the data source HonestJohn.co.uk reported an increase in the divergence for diesel cars, from 7.6% to 41.7% between 2001 and 2015, while the German Spritmonitor reported an increase from 8.0% to 42.2%. Divergences for HEV are based on Spritmonitor, because this is the only database providing continuous data for the period of investigation with sufficient data volume (3005 entries).

Starting from 2001 with three datasets, samples grew until 2015 covering six datasets which caused increasing uncertainties (see an example of uncertainty of CO_2 emission factors reflected in ranges of CO_2 emission scenarios in Fig. 4). Confidence intervals (CI95) in gap percentages, on the other hand, decreased in the same time down to 1.3% for diesel cars (Spritmonitor) and 1.4% for petrol cars (Spritmonitor), respectively. The average CI95 in gap percentages are 2.6% for both diesel and petrol cars as calculated with Spritmonitor data, which is the third biggest dataset with 134,463 entries (data covering 2001–2015).

Results of Tietge et al., (2016, 2017) show that real-world CO_2 emission values of both diesel and petrol cars increasingly moved away from type-approval figures, particularly after European CO_2 standards were introduced in 2008/2009, with diesel cars peaking at 42% divergence in 2015 (Fig. 1B).

We applied the real-world/type-approval deviation data from Tietge et al. (2017) to calculate the real-world CO_2 emissions of all newly registered petrol, diesel, and HEV in Europe, by combining the data from Fig. 1A and 1B. Fig. 1C presents these real-world emissions, showing that real-world CO_2 emissions of petrol cars decreased until 2012 and increased since then. Diesel car CO_2 emissions, however, didn't decrease since the year 2001, for the last 14 years of the period of investigation (Fig. 1C). Diesel and petrol car CO_2 emissions were hardly distinguishable since 2011 (Fig. 1C). The interim maximum of the year 2004 in petrol car emissions is caused by an interim gap maximum (Fig. 1B). HEV had the lowest type-approval and real-world CO_2 emissions, despite their comparatively high gap (see Fig. 1B). Type-approval to real-world (RW) divergences are highest for hybrid electric cars (Fig. 1B), because in-laboratory driving cycles begin with 100% state of charge (SOC) of the battery, while in reality the combustion engine has to recharge the battery (Mock et al., 2012). Real-world HEV emissions were, however, lower than petrol and diesel emissions by around 35 g CO_2/km, which is more than the reduction of CO_2 values achieved by efficiency improvements in petrol and diesel cars in 20 years.

2.2. Scenario calculations

In order to more specifically assess the effectiveness of the European diesel boom on reducing the overall climate impact of the passenger car fleet, we calculate the expected lifetime CO_2-eq emissions of all European passenger cars (use phase only) registered between 1995 and 2015, and compare this historical case with two alternative scenarios: a "constant 1995" scenario; and an "alternative mitigation" scenario, both of which are described in more detail below.

2.2.1. Fleet composition in each scenario

The annual total vehicle registrations for EU-15 considered and respective market shares according to different fuel types, for each of the scenarios, are presented in Fig. 2. New registrations data and share of diesel for the historic baseline scenario was taken from ACEA (2017). Increase of petrol hybrid cars in the alternative scenario equals that observed in Japan and data for 2014 and 2015 have been extrapolated from change of the previous two years (ICCT, 2015b).

The "constant 1995" scenario simply assumes that the percentages of petrol and diesel vehicles among new vehicle registrations remained constant at their 1995 levels, while all other factors evolved as in the historical case. This represents a situation in which the European diesel boom was avoided, but no other action was taken to mitigate CO_2 emissions from the European passenger vehicle sector. This scenario is built around the fact that the diesel car boom has been politically initiated in Europe by e.g. continuously granting tax advantages to diesel fuel (Cames and Helmers, 2013). The vehicle weight and power growth in European new car registrations since 2001 (ICCT, 2015a) might have been partly avoided without policies pushing diesel technology because of possible rebound-effects induced (Helmers, 2010), albeit such savings are not considered in the constant 1995 and the alternative scenario.

On the other hand, the "alternative mitigation" scenario represents another possible CO_2 mitigation pathway which Europe could have taken during 1995–2015 (Fig. 2). It is based on available technology during this time period and a comparison with Japan, a highly industrialized country with a regulation strictly and successfully reducing emissions. The scenario is based on the assumption that the tax advantages for diesel fuel over petrol were reduced starting in 1995, and instead granted to LPG and NG because of lower CO_2 emissions, thus decreasing diesel car registrations. LPG and NG have been known as alternative fuels for vehicles since the oil crisis in the 1970s (Helmers, 2009). We assume that, in contrast to Japan, where diesel cars were phased out almost entirely, diesel cars would have reached a low of 11.6% of new registrations in 2006 and remained at this value. This development is in accordance with the long-term diesel share of the European market prior to 1995 (Cames and Helmers, 2013). We further assume that European regulators would have incentivized the domestic car industry to develop petrol hybrid electric vehicles (HEV) as happened in Japan. The GHG mitigation potential of this technology was already known in the late 1990s (Cames and Helmers, 2013). Accordingly, we base our alternative scenario on the market penetration of HEV observed in Japan, which increases from 2008 onwards (JAMA, 2015, 2016). The share of LPG plus CNG cars peaked at an 11% market share in 2006, declining after 2008 to 4% in 2015 has a result from the increasing market penetration of HEV.

Since there is a lack of detailed information on European level for the Euro class of new registered cars, here we assumed that all cars correspond to the newest Euro standard of the respective year.

2.2.2. Emissions factors

Real-world data of the divergence between type-approval and real-world CO_2 emission values in Europe was collected and analysed as mentioned in the previous section 2.1. From this large dataset it was possible to derive the necessary emission factors to accomplish this analysis. Average divergence values presented in Fig. 1B were used here to adjust type-approval CO_2-emissions of newly-registered vehicles as presented in Fig. 1A. Prior to the year 2001, the divergence between type-approval and real-world emissions for 2001, +9.0% in case of diesel and +8.0% in case of petrol cars, were used for the years 1995–2000.Type-approval to RW divergences are highest for hybrid electric cars (Fig. 1B), because in-laboratory driving cycles begin with 100% state of charge (SOC) of the battery, while in reality the combustion engine has to recharge the battery (Mock et al., 2012).

To determine the baseline CO_2 emissions in COPERT we needed first to determine real-world fuel consumption factors. These were derived from our real-world CO_2 emissions (Fig. 1C) based on the equations and default values provided by EEA (2018). The resulting values are presented in Table 1.

CO_2-equivalents caused by BC emissions of diesel emissions have been considered for the climate impact evaluation over the time period considered.

Emission data related to standardized cycles like the New European Driving Cycle (NEDC) are subject to possible emission cheating, as it has been proven in recent literature dealing with RW emissions particularly when applying portable emissions measurement systems

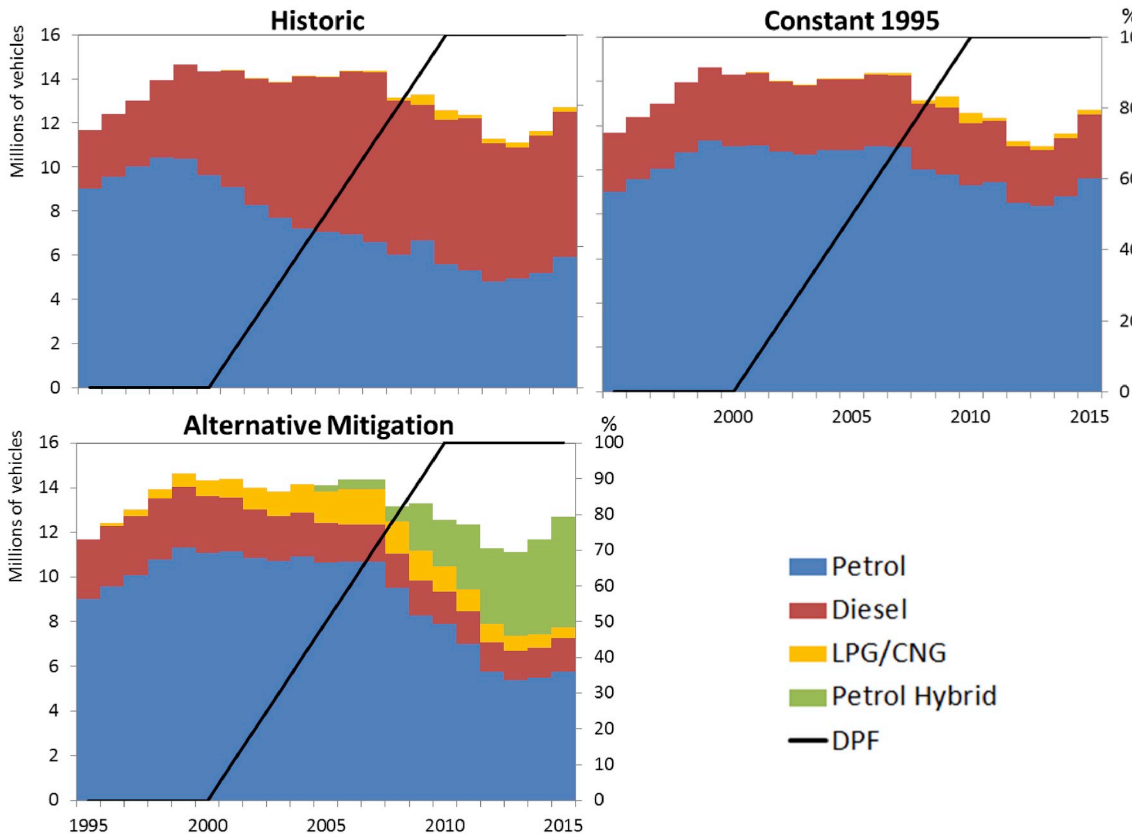

Fig. 2. New passenger car registrations per fuel type in Europe (EU-15) for the three considered scenarios. Also shown assumed percentage of DPF (diesel particulate filter) penetration rates in % (see subsection 2.2.2).

(PEMS) (Degraeuwe & Weiss 2017). Emission data based on laboratory conditions (dynamometer) are often unrealistically low (Borken-Kleefeld et al., 2014a, 2014b). In this analysis we use a slightly higher real-world result based on several studies (see values and respective references on Table 2).

Real-world PM emission data from on-road vehicle emissions remote sensing have been published (Tate, 2013, 2015). These measurements have high variance, but we extracted median results reported for diesel vehicles following emission standard Euro 2–4 quantified by Tate (2013, 2015), see Table 2. A sharp decrease in diesel car PM emissions from Euro 3 to Euro 5 (Tate, 2013, 2015) reflects the market penetration of DPFs (see Fig. 2). Non-exhaust PM and resuspended road dust interfere with remote sensing measurements at the low end of PM concentrations, for instance when measuring petrol vehicles and modern diesel cars (Euro 5–6), but this measurement artefact is limited to $<$ 1 mg/km in the data at hand (Tate, 2013, 2015). Accordingly, this concentration level cannot be considered for modelling here (see also Ježek et al., 2015). Real-world PM emission data distinguishing between Euro standards are rare in the scientific literature but a summary of available results is shown in Table 2. Analytical representativity of the data collected in Table 2 is not always comparable. In this context, however, it is interestingto note that Ligterink's (2017) results are close to the averages calculated (Table 2) which is due to the fact that they represent averages from urban, rural, and motorway measurements. Tate's (2013, 2015) emissions are lowest in the context of real-world PM emissions. This may be due to the fact that the measurements were taken several years after the implementation of DPFs, when a number of originally non-DPF diesel cars may have been retrofitted with a filter (TFL, 2017). Because we use recent PM emission measurements (see Table 2) to estimate historical PM emissions, the results should therefore be viewed as a conservative estimate of historical PM emissions.

The EEA emissions inventory guidebook (EEA, 2018) recommends different BC fractions in PM emissions of diesel vehicles according to the Euro class (Table 2). According to this source, BC in PM emissions of diesel cars with DPF are down to 10 and 20% (we assumed the later), while PM emitted by Euro 1–2 and Euro 3 onwards petrol cars contains 25 and 15% BC, respectively (EEA, 2018). Modern direct injection (DI) petrol cars can have elevated PM and particularly PN (Particle Number) emissions (Myung and Park, 2012) as well as higher BC concentrations in the PM emitted (Chan et al., 2016), but separate emission factors for petrol DI engines were not used in this study. DI engines have been introduced to the European car market since 2008, reaching a market share of around 40% among petrol cars by 2015 (ICCT, 2016). Chan et al. (2016), however, confirm that modern petrol DI cars without a particulate filter remain below the Euro 6 PM threshold of 5 mg/km. This is confirmed by Vouitsis et al. (2017), who proposed between 0.9 and 3 mg PM/km for DI petrol cars. PM emissions of DI petrol cars, which in the evaluation period all came without filters, are accordingly in the order of magnitude of a Euro 5/6 diesel car with DPF (Table 2).

CO_2-equivalent emissions for BC are calculated using the GWP100 value from Bond et al. (2013) of 900. We assume a constant lifetime mileage of 200,000 km per vehicle, as recommended by Weymar and Finkbeiner (2016). Our estimates of total committed emissions of newly registered vehicles for each year are subject to some uncertainty. In this analysis, we quantify the ranges of our scenarios arising from uncertainty in real-world CO_2 emission factors (represented as the standard deviation of the real-world emission factors), and the uncertainty in the GWP100 value of BC, for which we use low, central, and high values of 100, 900, and 1700 respectively (Bond et al., 2013). We chose the smaller GWP100 value for BC over the larger GWP20 value, since the former is the metric which is used as the standard metric under the Kyoto Protocol.

Table 3
Assumptions made in COPERT for circulation activity.

Driving mode	Share	Speed (km/h)
Urban Peak	15%	12
Urban OffPeak	25%	35
Rural	40%	60
Highway	20%	90

The total CO_2-eq based on the sum of real-world CO_2 and real-world BC derived from real-world PM is shown in Fig. 1D. These values illustrate the total of emissions factors used in the scenarios of this study and show a different perspective of Europe's diesel car boom as a climate protection measure. From 1995 to 2000, when European diesel cars lacked DPFs, diesel vehicles were extremely unfavourable for climate mitigation. After 2000, emissions from the two competing technologies have shown similar radiative forcing effects from both CO_2 and BC. In this calculation, no deterioration (malfunction due to aging, e.g. of DPF) effects are considered. Little is known about deterioration effects so far; passenger cars are usually treated as being in working order over the entire life when it comes to emissions modelling. The only comprehensive study available on deterioration effects points out increases in NO_x emissions over mileage of 200,000 km using remote sensing measurements, but PM emissions were not covered (Chen and Borken-Kleefeld, 2015). Pillot et al. (2014) tested 168 aged diesel cars randomly selected from French roads and found 1–4 engine defects in three quarters of the vehicles, which significantly increased PM emissions. In conclusion, and even without considering possible emission increases due to deterioration: At no time between 1995 and 2015 diesel cars have shown significant advantages in CO_2equivalent emissions over petrol cars in Europe.

The quantification of CO_2-equivalents emitted by diesel and petrol cars in the constant 1995 and alternative mitigation scenarios is based on the same real-world emissions as applied in the historical scenario (Fig. 1C). CO_2-emissions of HEV are based on historical averages in Europe (ICCT, 2016). Replacing petrol by LPG and NG results in CO_2 emission advantages of 19% (LPG) and 27% (NG), respectively (Helmers, 2009). Converted cars, however consume additional petrol during the warm-up phase. Considering this additional petrol consumption results in 14% (LPG cars) or 16% (NG cars) CO_2 savings over petrol cars (Helmers, 2009), respectively (average: 15%, applied for modelling here). BC emissions of HEV, LPG as well of NG cars are lower compared to petrol cars (Table 2).

2.3. Emissions modelling

Real-world CO_2 and PM emissions for each of the scenarios was determined with COPERT v5.1.1 (Ntziachristos et al., 2009; Emisia, 2018) that was specifically developed as a tool to support national experts of the European member states in the calculation of emissions from road transport for their inventories. This model facilitates the calculation where details of fleet and driving modes can be included, also accounting from non-exhaust and evaporation emissions for several pollutants. In this study only hot exhaust emissions were calculated, from fossil fuel combustion. The model also offers the possibility to determine emissions as a result of four different driving modes with different speeds. However, because in this analysis we have only average emission factors (as described in previous section), emissions were determined for only one driving mode with an assumed average driving speed of 50 km/h, and yearly mileage of 12,500 km (Weymar and Finkbeiner, 2016). For our calculations, the yearly stock of vehicles and the emission factors for fuel consumption and PM were changed accordingly to the real-world data collected as described above.

3. Results and discussion

3.1. Historic case: default COPERT vs real-world

By default, emissions with COPERT are calculated using the EEA recommendations in terms of emission factors and average fuel specifications. Here, lifetime CO_2 and BC (hot) emissions of passenger cars were determined with this model for the fleet assumed in our historic baseline scenario, keeping a set of default (Def) emission factors (EF) instead of the real-world (RW) used for our scenario analysis (see supplement material for details).

When running this emission model there are several possibilities to obtain a set of emission factors and fuel consumption that here we refer as “default”. Such factors are related to the speed assumed in different driving modes, of which, in COPERT, there are a total of 4: urban peak and off-peak, rural and highway. However, to be able to compare such emissions with our simulations it was necessary to determine emissions for one driving mode alone. Still, in an attempt to obtain "default" values representative of an average driving profile, the speed was initially kept as provided by the model and a combination of shares in each of the driving modes was selected (see Table 3). This combination was done in a way that when considering one driving mode the average speed would be 50 km/h, equal to that assumed to be representative of the real-world calculations. The average of these default EF for all vehicle segments was determined and the provided single implied fuel consumption and PM emission factor was used (with average speed of 50 km/h) to determine CO_2 and BC emissions for one driving mode.

The results are presented in Fig. 3 below in comparison with the baseline RW emissions from our historic scenario. The overall results show that, in the conditions described above, COPERT CO_2 emissions are lower than our RW emissions for petrol and diesel vehicles. However, these differences are negligible at the end of the analysed period. Still, it is important to mention that in our calculations of real-world emissions, it was not possible to include a detailed and weighted contribution from each driving mode. One important finding though is the high difference found in the BC values that reflect the different assumption of DPF implementation. While in the real-world conditions DPF are assumed to slowly be introduced in the market fleet, in COPERT this is not yet possible. Hence, the fast decrease of RW emissions from 2001 onwards is not replicated by the COPERT values (Fig. 3). At the end of the analysed period, when all cars in fleet have DPFs, both calculations show similar results.

3.2. Scenario calculations

The committed CO_2 and BC emissions over the full on-road lifetime of all new passenger cars registered in Europe (EU15) between 1995 and 2015 are presented in Table 4 for each of the three scenarios: historic baseline, constant 1995, and alternative mitigation. The scenarios are described in Section 2, and respective vehicle registration data is taken from Fig. 2.

We quantified CO_2-emissions separately for the year 2008 in order to get a literature comparison: Our model results in 0.448 Gt CO_2 equivalents for the year 2008 (EU-15), assuming a fleet of cars on road constituted by new vehicles since 1995. EEA (2011) reports 0.712 Gt CO_2 equivalents emitted in the EU-27 by road transport in the year 2008, recalculated for EU-15 and the passenger car share resulting in 0.427 Gt CO_2 equivalents. Hendricks et al. (2017) quantified 1.135 Gt CO_2 for the land-based transport in geographical Europe. Adding 20% CO_2 equivalents from non-CO_2 GHG (EEA, 2011), assuming that maritime transport contributes some 15% of the emitted CO_2eq of land-based transport (EEA, 2011), and quantifying the share of the EU-15 countries, we calculated 0.555 Gt CO_2 equivalents from Hendricks et al. (2017), as emitted from passenger cars in the year 2008, which can only be an orientation, but confirm the right order of magnitude of our modelling result.

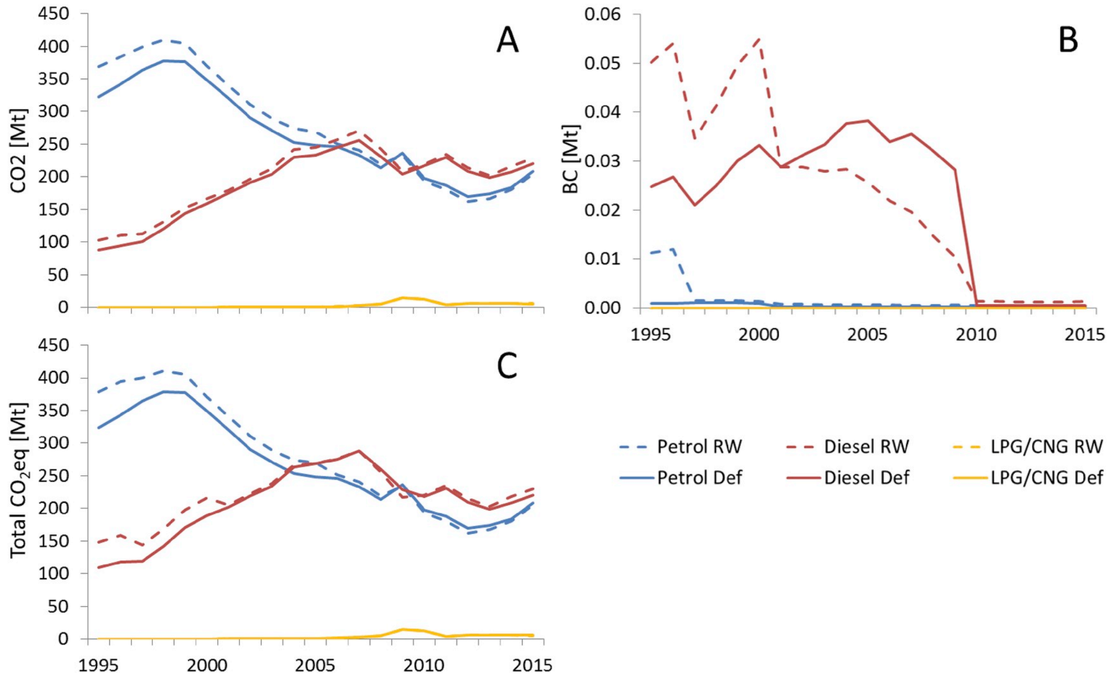

Fig. 3. Real-world (RW) and COPERT "default" (Def) lifetime committed emissions (in Mt) for CO_2 (A) and BC (B) and Total CO_2-eq (C), for new passenger cars of different fuel types, registered between 1995 and 2015 in the EU-15. (Emissions of RW and Def from LPG/CNG vehicles are quite similar, and close to zero for BC, which results in an overlap of the corresponding yellow lines in the graphs above.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

According to Table 4, the climate impact of the European diesel boom between 1995 and 2015 was approx. 45 Mt CO_2 equivalents, or about a 0.4% increase compared with the constant 1995 scenario. The reduction in CO_2 emissions due to the diesel boom (compared with the constant 1995 scenario) was offset by the increased emissions of BC during the period in which diesel vehicles were not fitted with particulate filters. When using the higher GWP20 value for BC, instead of the GWP100 used here, the historical scenario would have marginally higher GHG emissions than the constant 1995 scenario.

The alternative mitigation scenario would have produced a climate benefit of 354 Mt CO_2-eq, or a 3.4% reduction in total CO_2 equivalent emissions, compared with the historic scenario. The ranges of values calculated for all three scenarios—historical, constant 1995, and alternative mitigation—overlap significantly. These ranges are dominated by the range in the real-world CO_2 emission factors for passenger vehicles, which spans a range of about 4000 Mt CO_2 in all scenarios. The uncertainty range in GWP100 estimates of BC has an impact of about 500 Mt CO_2 equivalents, which is of similar magnitude to the overall climate benefit of the alternative mitigation scenario. In this sense, all three scenarios are virtually indistinguishable from each other in terms of their total climate benefit over the period 1995 to 2015 within the ranges calculated here.

Annual committed (vehicle lifetime) emissions from 1995 to 2015 and their ranges are presented for CO_2 and for BC in Fig. 4. In each case, the committed emissions for each year (over the full vehicle lifetime of 200,000 km, i.e. a total of 16 years (Weymar and Finkbeiner, 2016) are shown for the year in which the vehicles were first registered. The scenario range for BC is much larger during the earlier years, when diesel vehicles were not fitted with particulate filters, while the range due to high and low real-world CO_2 emission factors remains high

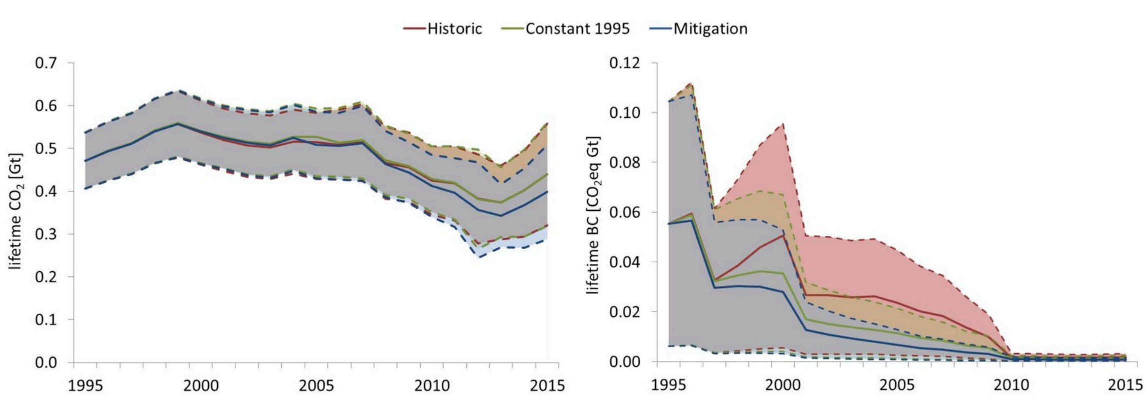

Fig. 4. Annual committed GHG emissions (in Gt) for CO_2 (left pane) and BC (in CO_2 eq, right pane) for new passenger cars registered between 1995 and 2015 in the EU-15 in the three scenarios analysed in this study: Historic (red), Constant 1995 (green) and Alternative Mitigation (blue). Central values (solid lines) are complemented with the ranges from low and high values (dashed lines) calculated for each scenario as described in the text are also presented (shaded areas in respective colours).

Table 4
Total committed lifetime emissions of CO_2, BC (black carbon), and total CO_2-eq for vehicles registered between 1995 and 2015 for each scenario, with respective low and high values. CO_2-eq: CO_2 equivalents.

Scenario	Species	central estimate (Mt)	scenario range (Mt)	
			Lowest	Highest
Historic	CO_2	10062	8327	11761
	BC (CO_2-eq)	483	54	913
	total CO_2-eq	10545	8381	12673
Constant 1995	CO_2	10140	8395	11844
	BC (CO_2-eq)	360	40	680
	total CO_2-eq	10500	8435	12524
Alternative mitigation	CO_2	9892	8215	11554
	BC (CO_2-eq)	299	33	565
	total CO_2-eq	10191	8248	12119

during the entire period. Despite this large range, a downward trend is apparent in annual committed emissions. However, this downward trend is not consistent: Before 2000 and after 2012, (yearly) lifetime committed emissions appear to increase slightly.

Comparison of emissions and numbers of new vehicle registrations shows that periods of growing GHG emissions coincided with increases in the number of vehicle registrations. The rise in registrations between 1995 and 1999 coincided with a period in which real-world emission factors were declining (Fig. 4), meaning that the modest improvements in fuel efficiency during this time were more than offset by increased numbers of new vehicles. The rise in registrations between 2013 and 2015 coincided with a period in which real-world emission factors remained relatively constant. During the period 1999 to 2013, real-world CO_2 emission factors and the annual number of new vehicle registrations both declined. Clearly, the committed GHG emissions from passenger cars each year are strongly influenced by the number of new vehicle registrations in that year.

In 2015, annual new vehicle registrations were still lower than pre-2008 levels. If the positive trends in new vehicle registrations and the flat trend in real-world CO_2 emissions both continue, as they have since 2013, annual committed GHG emissions from newly registered European passenger vehicles will continue to rise in the coming years.

4. Conclusions

The "diesel boom" that started in the European Union in the mid-1990s most likely delivered no climate benefit in terms of the total CO_2-eq emissions between 1995 and 2015. The modest savings in CO_2 emissions from the promotion of more fuel-efficient diesel vehicles in the 1990s and early 2000s were most likely cancelled out due to radiative forcing from increased emissions of black carbon during this period, in which most diesel vehicles were not fitted with particulate filters. Since about 2001, diesel and petrol vehicles each produce similar real-world GHG emissions, including CO_2 and black carbon.

Limited CO_2 equivalents savings (a 3.4% reduction in total CO_2 equivalent emissions compared with a scenario in which the ratio of diesel to petrol engines in newly registered vehicles was kept constant at 1995 values) would have been possible by promoting petrol hybrids instead of diesels as it has been done in Japan and, earlier, fuels based on fossil methane, propane, and butane (LPG and CNG). From today's perspective, Europe chose the wrong alternative by promoting diesel cars instead of the other powertrains and fuels which were available at the time. This is particularly true when also considering the adverse health effects due to emissions from diesel vehicles (e.g., Anenberg et al., 2017; Jonson et al., 2017).

Our data, however, also suggest that there is no fundamental climate benefit when switching from one fossil fuel to another. Real-world CO_2 emissions from European passenger cars may even be rising again due to a combination of increased annual vehicle registrations and a stagnation in real-world CO_2 emission values for all types of vehicles, including diesel, petrol, and hybrid vehicles. In order to significantly reduce GHG emissions from the European passenger vehicle fleet, either the total size of the fleet must be decreased, or real-world CO_2 emission values must be reduced, either by more stringent CO_2 standards and better policy enforcement or by introducing a significant number of low emission vehicles, such as battery electric cars powered using electricity from renewable energy sources.

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Appendix A. Supplementary data

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References

ACEA, 2016. The Automobile Industry Pocket Guide 2016-2017. http://www.acea.be/uploads/publications/POCKET_GUIDE_2015-2016.pdf, Accessed date: 9 May 2017.
ACEA, 2017. New Passenger Car Registrations Breakdown by Share of Diesel. https://www.acea.be/uploads/statistic_documents/Share_of_diesel_in_new_cars_in_West_Europe_%281990-2017%29.xlsx, Accessed date: 9 May 2017.
Ajanovic, A., 2011. The effects of dieselization of the European passenger car fleet on energy consumption and CO_2 emissions. In: Proceedings of the 34th IAEE International Conference, Institutions, Efficiency and Evolving Energy Technologies, . https://www.iaee.org/en/publications/proceedingsdetail.aspx?id=5043, Accessed date: 10 October 2018.
Ajanovic, A., Haas, R., 2012. The role of efficiency improvements vs. price effects for modeling passenger car transport demand and energy demand—lessons from European countries. Energy Pol. 41, 36–46. https://doi.org/10.1016/j.enpol.2011.03.086.
Ajanovic, A., Haas, R., 2014. Promoting the dieselization of the European fleet: was it worth it? In: Presentation, New York City IAEE International Conference (June 15-18, 2014), . http://www.usaee.org/usaee2014/submissions/Presentations/Ajanovic%20IAEEE-2014.pdf, Accessed date: 10 October 2018.
Anenberg, S.C., Miller, J., Minjares, R., Du, L., Henze, D.K., Forrest Lacey, F., Malley, C.S., Emberson, L., Franco, V., Klimont, Z., Heyes, C., 2017. Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. Nature. https://doi.org/10.1038/nature22086. May 2017.
Böck, R., 2006. Automotive catalysts. In: Zereini, F., Alt, F. (Eds.), Palladium Emissions in the Environment. Springer Berlin Heidelberg, pp. 3–21 (Chapter 1).1.
Bond, T.C., Sun, H., 2005. Can reducing black carbon emissions counteract global warming? Environ. Sci. Technol. 39, 5921–5926.
Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C.S., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. J. Geophys. Res. Atmos. https://doi.org/10.1002/jgrd.50171.
Borken-Kleefeld, J., Fuglestved, J., Berntsen, T., 2014a. Mode, load, and specific climate impact from passenger trips. Environ. Sci. Technol. 47 (14), 7608–7614.
Borken-Kleefeld, J., Fuglestved, J., Berntsen, T., 2014b. Supporting information for: mode, load, and specific climate impact from passenger trips. Environ. Sci. Technol. 47 (14), 7608–7614. http://pubs.acs.org/doi/suppl/10.1021/es4003718/suppl_file/es4003718_si_001.pdf, Accessed date: 16 May 2017.
Cames, M., Helmers, E., 2013. Critical evaluation of the European diesel car boom – global comparison, environmental effects and various national strategies. Environ. Sci. Eur. 25 (15), 22. Available from: http://www.enveurope.com/content/pdf/2190-4715-25-15.pdf.
Carslaw, D.C., Martin, L., Williams, M.L., Tate, J.E., Beevers, S.D., 2013. The importance of high vehicle power for passenger car emissions. Atmos. Environ. 68, 8–16. https://doi.org/10.1016/j.atmosenv.2012.11.033.
CDP, 2016. Guidance Methodology for Estimation of Scope 3 Category 11 Emissions for Oil and Gas Companies. 29/01/16 First Version of Guidance Methodology. https://www.cdp.net/Documents/Guidance/2016/CDP-Scope-3-c11-Guidance-Oil-Gas-

2016.pdf, Accessed date: 12 May 2017.
Chan, T.W., Saffaripour, M., Liu, F., Hendren, J., Thomson, K.A., Kubsh, J., Brezny, R., Rideout, G., 2016. Characterization of real-time particle emissions from a gasoline direct injection vehicle equipped with a catalyzed gasoline particulate filter during filter regeneration. Emiss. Control Sci. Technol 2, 75–88. https://doi.org/10.1007/s40825-016-0033-3. (2016).
Chen, Y., Borken-Kleefeld, J., 2014. Real-driving emissions from cars and light commercial vehicles - results from 13 years remote sensing at Zurich/CH. Atmos. Environ. 88, 157–164 (2014).
Chen, Y., Borken-Kleefeld, J., 2015. NOx emissions from diesel passenger cars worsen with age. Environ. Sci. Technol. 50, 3327–3332 2016.
Defra, 2012. Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting. Version: 1.0, updated: 28/05/2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69554/pb13773-ghg-conversion-factors-2012.pdf, Accessed date: 12 May 2017.
Degraeuwe, B., Weiss, M., 2017. Does the New European Driving Cycle (NEDC) really fail to capture the NOX emissions of diesel cars in Europe? Environ. Pollut. 222, 234–241. https://doi.org/10.1016/j.envpol.2016.12.050.
Dieselnet.com, 2017. EU: Cars and Light Trucks Emission Standards. https://www.dieselnet.com/standards/eu/ld.php, Accessed date: 14 May 2017.
EEA, 2011. Greenhouse Gas Emissions in Europe: a Retrospective Trend Analysis for the Period 1990–2008. EEA Report No 6/2011. pp. 124. https://www.eea.europa.eu/publications/ghg-retrospective-trend-analysis-1990-2008/at_download/file, Accessed date: 27 August 2018.
EEA, 2012. European Environmental Agency: Annual European Union Greenhouse Gas Inventory 1990–2010 and Inventory Report 2012. Submission to the UNFCCC Secretariat. 2012. Available from:. . http://www.eea.europa.eu/publications/european- union-greenhouse-gas-inventory-2012, Accessed date: 4 April 2016.
EEA, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013. Technical Guidance to Prepare National Emission Inventories. https://www.eea.europa.eu/publications/emep-eea-guidebook-2013/at_download/file, Accessed date: 9 June 2017.
EEA, 2014. Monitoring CO_2 EmissioCns from New Passenger Cars in the EU: Summary of Data for 2013. https://www.eea.europa.eu/publications/monitoring-co2-emissions-from-passenger/at_download/file, Accessed date: 9 May 2017.
EEA, 2016a. European Environmental Agency: Air Quality in Europe — 2016 Report. EEA Report No 28/2016, 88 pp. . https://www.eea.europa.eu/publications/air-quality-in-europe-2016/at_download/file, Accessed date: 8 May 2017.
EEA, 2016b. Monitoring CO_2 Emissions from New Passenger Cars and Vans in 2015. EEA Report No 27/2016. . https://www.eea.europa.eu/publications/monitoring-co-2-emissions-from/at_download/file, Accessed date: 13 May 2017.
EEA, 2017. Fuel Efficiency Improvements of New Cars in Europe Slowed in 2016. News Published 20 Apr 2017, last modified 24 Apr 2017. https://www.eea.europa.eu/highlights/fuel-efficiency-improvements-of-new, Accessed date: 7 May 2017.
EEA, 2018. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016. 1.A.3.b.I-iv Road Transport 2018. https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view, Accessed date: July 2018.
Emisia, S.A., 2018. COPERT Data. http://www.emisia.com/utilities/copert/ COPERT v5.1.1. downloaded on June 8 2018.
EU, 2005. Implementing the Community Strategy to Reduce CO2 Emissions from Cars: Fifth Annual Communication on the Effectiveness of the Strategy. Brussels, 22.6.2005 COM(2005). http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2005:0269:FIN:en:PDF, Accessed date: 7 July 2017.
EU, 2012. Commission Staff Working Document Impact Assessment, Part II. Accompanying the Documents: “Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EC) No 443/2009 to Define the Modalities for Reaching the 2020 Target to Reduce CO2 Emissions from New Passenger Cars” and “Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EU) No 510/2011 to Define the Modalities for Reaching the 2020 Target to Reduce CO2 Emissions from New Light Commercial Vehicles”. https://www.eumonitor.nl/9353000/1/j4nvgs5kjg27kof_j9vvik7m1c3gyxp/vj1f4gy9pdzt/f=/12733_12_add_2.pdf, Accessed date: 30 November 2017.
EU, 2014. Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 Amending Regulation (EC) No 443/2009 to Define the Modalities for Reaching the 2020 Target to Reduce CO2 Emissions from New Passenger Cars. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.103.01.0015.01.ENG , Accessed date: 30 November 2017.
EU, 2016. EU Legislation on Passenger Car Type Approval and Emissions Standards. European Commission - Fact Sheet, Brussels 8 December 2016. http://europa.eu/rapid/press-release_MEMO-16-4269_en.htm, Accessed date: 8 May 2017.
Fontaras, G., Zacharof, N.G., Ciuffo, B., 2017. Fuel consumption and CO_2 emissions from passenger cars in Europe - laboratory versus real-world emissions. Prog. Energy Combust. Sci. 60, 97–131. (2017). https://doi.org/10.1016/j.pecs.2016.12.004.
Fritsche, U.R., 2007. Endenergiebezogene Gesamtemissionen für Treibhausgase aus fossilen Energieträgern unter Einbeziehung der Bereitstellungsvorketten. Kurzbericht im Auftrag des Bundesverbands der deutschen Gas- und Wasserwirtschaft e.V. (BGW). http://www.iinas.org/tl_files/iinas/downloads/GEMIS/2007_thg_fossil_BGW.pdf, Accessed date: 12 May 2007.
Helmers, 2009. The Car of the Future. Wiley-VCH 2009. 204 pages.
Helmers, 2010. Bewertung der Umwelteffizienz moderner Autoantriebe – auf dem Weg vom Diesel-Pkw-Boom zu Elektroautos. Umweltwiss Schadst Forsch 22, 564–578 (2010).
Hendricks, J., Righi, M., Dahlmann, K., Gottschaldt, K.D., Grewe, V., Ponater, M., Sausen, R., Heinrichs, D., Winkler, C., Wolfermann, A., Kampffmeyer, T., Friedrich, R., Klötzke, M., Kugler, U., 2017. Quantifying the climate impact of emissions from land-based transport in Germany. Transport. Res. Part D (in press). https://doi.org/10.1016/j.trd.2017.06.003.
Hooftman, N., Oliveira, L., Messagie, M., Coosemans, T., van Mierlo, J., 2016. Environmental analysis of petrol, diesel and electric passenger cars in a Belgian urban setting. Energies 9, 84. https://doi.org/10.3390/en9020084. 2016.
ICCT, 2015a. European Vehicle Market Statistics. Pocketbook 2015/16. http://www.theicct.org/sites/default/files/publications/ICCT_EU-pocketbook_2015.pdf Accessed June 14, 2017.
ICCT, 2015b. Light-duty Vehicle Efficiency Standards. Fact Sheet Japan, January 2015. http://www.theicct.org/sites/default/files/info-tools/pvstds/Japan_PVstds-facts_jan2015.pdf, Accessed date: 24 July 2017.
ICCT, 2016. European Vehicle Market Statistics. Pocketbook 2016/17. http://www.theicct.org/sites/default/files/publications/ICCT_Pocketbook_2016.pdf, Accessed date: 24 July 2017.
Jacobson, 2005. Correction to ‘‘Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming’’. J. Geophys. Res. B 110, D14105. https://doi.org/10.1029/2005JD005888.
Jacobson, M.Z., Seinfeld, J.H., Carmichael, G.R., Streets, D.G., 2004. The effect on photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel vehicles. Geophys. Res. Lett. 31, L02116. https://doi.org/10.1029/2003GL018448.
JAMA, 2015. The Motor Industry of Japan 2015. Japan Automobiles Manufacturers Association. http://www.jama-english.jp/publications/MIJ2015.pdf, Accessed date: 13 May 2017.
JAMA, 2016. The Motor Industry of Japan 2016. Japan Automobiles Manufacturers Association. http://www.jama-english.jp/publications/MIJ2016.pdf, Accessed date: 13 May 2017.
Ježek, I., Drinovec, L., Ferrero, L., Carriero, M., Movnik, G., 2015. Determination of car on-road black carbon and particle number emission factors and comparison between mobile and stationary measurements. Atmos. Meas. Tech. 8, 43–55. https://doi.org/10.5194/amt-8-43-2015. 2015.
Jonson, J.E., Borken-Kleefeld, J., Simpson, D., Nyıri, A., Posch, M., Heyes, C., 2017. Impact of excess NO_x emissions from diesel cars on air quality, public health and eutrophication in Europe. Environ. Res. Lett. 12, 094017. https://doi.org/10.1088/1748-9326/aa8850.
Kadijk, G., Ligterink, N., van Mensch, P., Spreen, J., Vermeulen, R., Vonk, W., 2015. Emissions of Nitrogen Oxides and Particulates of Diesel Vehicles. TNO Report 2015-R10838. . http://publications.tno.nl/publication/34617056/4QHNNo/TNO-2015-R10838.pdf, Accessed date: 16 May 2017.
Knittel, C., 2012. Automobiles on steroids. Product attribute trade-offs and technological progress in the automobile sector. Am. Econ. Rev. 101, 3368–3399.
Kühlwein, J., German, J., Bandivadekar, A., 2014. Development of Test Cycle Conversion Factors Among Worldwide Light-duty Vehicle CO_2 Emission Standards. ICCT White paper, September 2014. pp. 68. https://www.theicct.org/publications/development-test-cycle-conversion-factors-among-worldwide-light-duty-vehicle-co2, Accessed date: 23 August 2018.
Ligterink, 2017. Real-world Vehicle Emissions. Discussion Paper 2017-06. International Transport Forum. https://www.itf-oecd.org/sites/default/files/docs/real-word-vehicle-emisions.pdf, Accessed date: 19 July 2018.
MLIT Ministry of Land, Infrastructure, Transport and Tourism, 2017. Development of Average JC08 Mode Fuel Efficiency of Gasoline Cars. http://www.mlit.go.jp/common/001178216.pdf, Accessed date: 25 November 2017.
Mock, P., German, J., Bandivadekar, A., Riemersma, I., 2012. Discrepancies between Type-approval and “real-world” Fuel-consumption and CO_2 Values. Assessment for 2001-2011 European Passenger Cars. Working paper 2012–02, 13 pp. http://www.theicct.org/sites/default/files/publications/ICCT_EU_fuelconsumption2_workingpaper_2012.pdf, Accessed date: 27 August 2018.
Mock, P., German, J., Bandivadekar, A., Riemersma, I., Ligterink, N., Lambrecht, U., 2013. From Laboratory to Road – a Comparison of Official and “real-world” Fuel Consumption and CO_2 Values for Cars in European and the United States. The International Council on Clean Transportation, Washington. http://www.theicct.org/sites/default/files/publications/ICCT_LabToRoad_20130527.pdf, Accessed date: 24 November 2017.
Motowidlak, U., 2016. Identification of behavioral changes in transport as a means for decarbonisation of the economy. In: Bąk, M. (Ed.), Transport Development Challenges in the Twenty-first Century. Springer. Proceedings in Business and Economics Springer International, Berlin, pp. 171–180.
Myung, C.L., Park, S., 2012. Exhaust nanoparticle emissions from internal combustion engines: a review. Int. J. Automot. Technol. 13 (1), 9–22.
Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. COPERT: a European road transport emission inventory model. In: Athanasiadis, I.N., Rizzoli, A.E., Mitkas, P.A., Gómez, J.M. (Eds.), Information Technologies in Environmental Engineering. Environmental Science and Engineering. Springer, Berlin, Heidelbergb. https://doi.org/10.1007/978-3-540-88351-7_37.
Pillot, D., Legrand-Tiger, A., Thirapounho, E., Tassel, P., Perret, P., 2014. Impacts of Inadequate Engine Maintenance on Diesel Exhaust Emissions, vol. 4. Transport Research Arena, Paris, pp. 1–10.
Rockström, J., Schellnhuber, H.J., Hoskins, B., Ramanathan, V., Schlosser, P., Brasseur, G.P., Gaffney, O., Nobre, C., Meinshausen, M., Joeri, R., Lucht, W., 2016. The world's biggest gamble. Earth’s Future 4, 465–470. https://doi.org/10.1002/2016EF000392.
Schipper, L., Céline, M.L., Fulton, L., 2002. Diesels in Europe - analysis of characteristics, usage patterns, energy savings and CO_2 emission implications. J. Transport Econ. Pol. 36 (2), 305–340.
Schipper, L., Deakin, E., McAndrews, C., 2011. Carbon dioxide emissions from urban road transport in Latin America: CO_2 reduction as a co-benefit of transport strategies. In: Rothengatter, W. (Ed.), Transport Moving to Climate Intelligence. Transportation

Research, Economics and Policy. Springer Science + Business Media, Berlin, pp. 111–127.
Shields, E., 2016. Particulate Matter (PM) Emissions from low greenhouse gas engine technologies. In: Presentation, September 28th, 2016, . https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/particulate_matter_emissions_from_low_greenhouse_gas_emission_technologies_erin_shields.pdf, Accessed date: 25 July 2017.
Shindell, D., Kuylenstierna, J.C., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously mitigating near-term climate change and improving human health and food security. Science 335, 183–189. https://doi.org/10.1126/science.121002.
Tate, 2013. Project Report: Vehicle Emission Measurement and Analysis - Cambridge City Council. Draft Document Version 1.0: 28th November 2013. University of Leeds, Institute for transport studies, pp. 65. https://www.cambridge.gov.uk/sites/default/files/documents/Cam_VEMS_ProjectReport_v1.0.pdf, Accessed date: 8 May 2017.
Tate, 2015. Real driving emissions (RDE): results from the 2015 remote sensing campaigns (UK). In: Presentation, Routes to Clean Air – Air Quality Conference IAQM. October 23rd, 2015, . https://www.slideshare.net/ITSLeeds/real-driving-emissions-uk-remote-sensing-results-2015, Accessed date: 16 May 2017.
TFL Transport for London, 2017. Fit a Filter: Fitting an Approved Filter to Your Exhaust Could Reduce Your Vehicle's Emissions Enough to Meet the Low Emission Zone (LEZ) Emissions Standards. https://tfl.gov.uk/modes/driving/low-emission-zone/ways-to-meet-the-standards/fit-a-filter, Accessed date: 1 December 2017.
Tietge, U., Díaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N., From laboratory to road, 2016. A 2016 Update of Official and "real-world Fuel Consumption and CO_2 Values for Passenger Cars in Europe. November 2016 white paper. http://www.theicct.org/laboratory-road-2016-update, Accessed date: 7 May 2017.
Tietge, U., Mock, P., Franco, V., Zacharof, N., 2017. From Laboratory to Road: Modeling the Divergence between Official and Real-world Fuel Consumption and CO_2 Emission Values in the German Passenger Car Market for the Years 2001–2014.
UNFCCC, 2015. UN Framework Convention on Climate Change. Adoption of the Paris Agreement (2015). Proposal by the President, Draft Decision -/CP.21. 2015. Available from:. http://unfccc.int/resource/docs/2015/cop21/eng/l01.pdf, Accessed date: 1 April 2016.
von Schneidemesser, E., Kuik, F., Mar, K.A., Butler, T., 2017. Potential reductions in ambient NO_2 concentrations from meeting diesel vehicle emissions standards. Environ. Res. Lett. 12, 114025. https://doi.org/10.1088/1748-9326/aa8c84.
Vouitsis, I., Ntziachristos, L., Samaras, C., Samaras, Z., 2017. Particulate mass and number emission factors for road vehicles based on literature data and relevant gap filling methods. Atmos. Environ. 168, 75–89.
Weymar, E., Finkbeiner, M., 2016. Statistical analysis of empirical lifetime mileage data for automotive LCA. Int. J. Life Cycle Assess. 21, 215–223. https://doi.org/10.1007/s11367-015-1020-6.