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SHIFTING GEARS: THE EFFECTS OF A FUTURE DECLINE IN DIESEL MARKET SHARE ON TAILPIPE CO_2 AND NO_X EMISSIONS IN EUROPE

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EXECUTIVE SUMMARY

Diesel vehicles currently account for more than half of new light-duty vehicle registrations in Europe. Previous ICCT analyses of the costs of attaining more stringent CO_2 emission standards assumed a constant diesel market share in future years. However, the diesel market share in Europe could decrease in future years as a result of a combination of forces, including changing consumer choices in the wake of the defeat device scandal; vehicle manufacturers shifting away from diesel technology in response to tighter NO_x emission standards and real-driving emissions testing; availability of cheaper and more powerful electric and hybrid cars; and government programs to discourage diesel vehicle use (e.g., by restricting their circulation, or increasing taxes on diesel fuel). A decreasing market share of diesel passenger cars could have broad implications for the cost of attaining CO_2 emission targets and the magnitude of fleetwide NO_x emissions. This paper analyzes the sensitivity of these parameters to potential decreases in the diesel passenger car market share in the EU.

With a smaller diesel market share, we find that the EU could achieve a hypothetical 70 g/km (as measured according to the New European Driving Cycle – NEDC) passenger vehicle CO_2 target in 2025 with both lower net cost and reduced NO_x emissions. This conclusion is drawn from three analyses: (1) a comparison of historical diesel market share and fleetwide CO_2 emissions in EU member states and other major vehicle markets; (2) newly developed cost curves describing the cost of compliance for different technologies with various future fleet average CO_2 targets in the EU, considering a range of possible changes in the market share of diesel passenger cars; and (3) tailpipe NO_x emissions under scenarios with varying diesel passenger car market shares. These findings indicate that decreasing the diesel passenger car market share in the EU would not affect compliance with tighter CO_2 emission targets in 2025 but would provide cost savings for manufacturers as well as air quality benefits.

Substantial fleetwide CO_2 emission reductions in the Netherlands, Germany, and France were achieved from 2001 to 2015 without major increases in diesel market share. Similar effects are seen for the U.S. and Japan. On average, over all vehicle segments in the EU, conventional diesel and gasoline cars show roughly the same level of CO_2 emissions per kilometer. Within a vehicle segment, though, diesel cars show lower levels of CO_2 per kilometer than gasoline. In the lower medium passenger car segment, for example, the average diesel car emits around 17% less CO_2 than the average gasoline car. However, the average CO_2 level of hybrid cars, excluding plug-in hybrids, is 32% lower than that of the average gasoline car within the same segment, as shown in Figure ES-1. Diesel cars typically come at a higher price than gasoline cars, as they are more expensive to manufacture. Hybrid cars, too, come at a higher price but this price premium for hybrids has declined in recent years. As a result, it is found that, within the lower medium segment analyzed, CO_2 emissions can be reduced by switching from gasoline to gasoline hybrid vehicles at a much lower price increase, expressed in price premium per g/km of CO_2 reduced, than switching from gasoline to diesel cars.

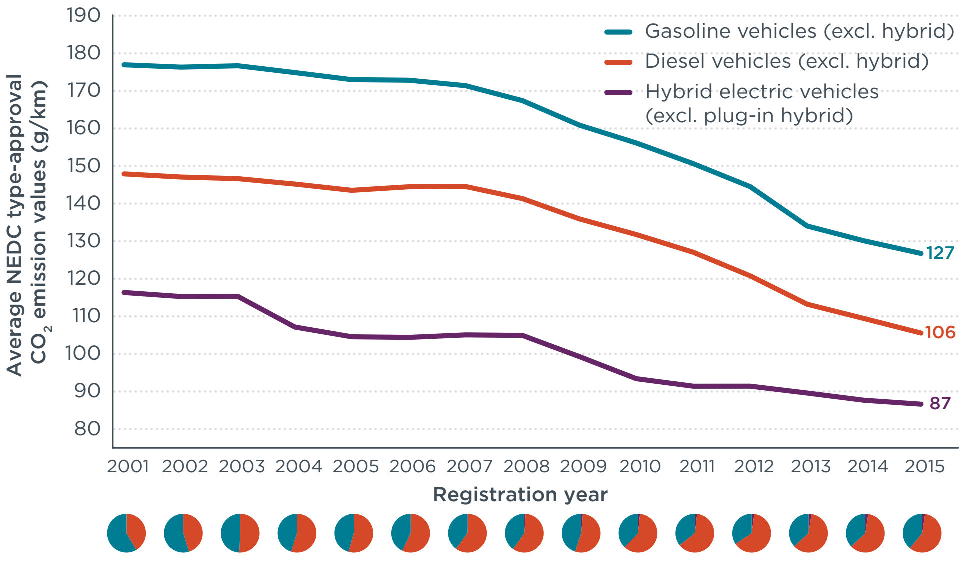

Figure ES-1. Sales-weighted average type-approval CO_2 emissions from EU lower medium passenger cars by fueling technology. Pie charts indicate the market share of gasoline, diesel and hybrid vehicles in each year. *(Mock, 2016).*

Newly developed cost curves that account for changes in the market share of diesel passenger cars demonstrate that reducing diesel market share can result in net cost savings for manufacturers, because the cost increases for additional gasoline technology are outweighed by moving from more expensive conventional diesel engines with complex exhaust aftertreatment systems to cheaper conventional gasoline engines with simpler pollution control devices.[1] Assuming a 70 g CO_2/km emission standard, based on the (NEDC) for new passenger cars in 2025, net compliance costs would decline by 10 to 280 euros per vehicle, using a 2014 baseline, if the diesel market share of new car sales declines from 56.5% to 15% as shown in Figure ES-2. The range in estimated compliance cost changes reflects two sets of assumptions, one reflective of an analysis scenario that assumes lower bound technology cost assumptions and one reflective of a corresponding upper bound technology cost scenario. These findings indicate that the net cost of CO_2 reduction for passenger cars in the EU is relatively insensitive to diesel market share, but it tends to decline with decreasing diesel market share.

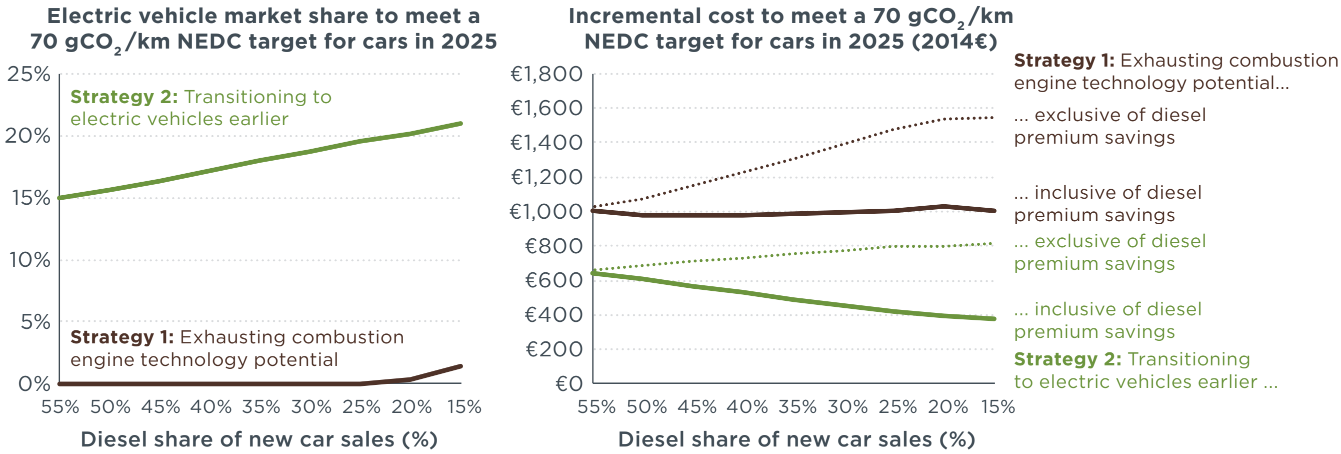

Figure ES-2. Change in electric vehicle market shares (left hand side) and compliance costs (right hand side) for meeting a 70 g/km NEDC target for cars in 2025 with different diesel market shares.

1 Note that diesel aftertreatment costs assumed in this study do not include additional costs that may be incurred to meet Euro 6 RDE requirements. Consideration of such costs would increase the cost savings associated with moving from diesel to gasoline vehicles.

In addition to reducing the cost of compliance with CO_2 standards, a shift from diesels to gasoline, hybrid, and electric vehicles could benefit air quality through reduced tailpipe emissions of air pollutants. Six NO_x emission scenarios model the effects of meeting a 70 g/km CO_2 target in 2025 and project NO_x emissions to 2030. The first three scenarios examine the impact of a smaller diesel market share under a baseline real-driving emissions (RDE) program, which reflects a worst case scenario without further development beyond the adopted first and second RDE packages shown in Figure ES-3. In contrast, the fourth through sixth scenarios examine the impact of a smaller diesel market share assuming an improved RDE program, specifically, Accelerated RDE+, which considers the expected third and fourth RDE packages as well as further improvements previously recommended by the International Council on Clean Transportation (ICCT). As shown, the NO_x emission benefits of a smaller diesel market share are larger under a baseline RDE program compared to an improved program, because diesel vehicles are expected to be much cleaner under an improved RDE program. By 2030, the NO_x benefits of a smaller diesel market share range from approximately 60,000 tons per year, equivalent to a 10%–11% emission reduction with Accelerated RDE+, to about 260,000 tons per year, equivalent to a 27%–28% emission reduction with baseline RDE. For context, the NO_x benefits of a smaller diesel market share are equivalent to the sum of all NOx emissions in a country of the size of the Netherlands.

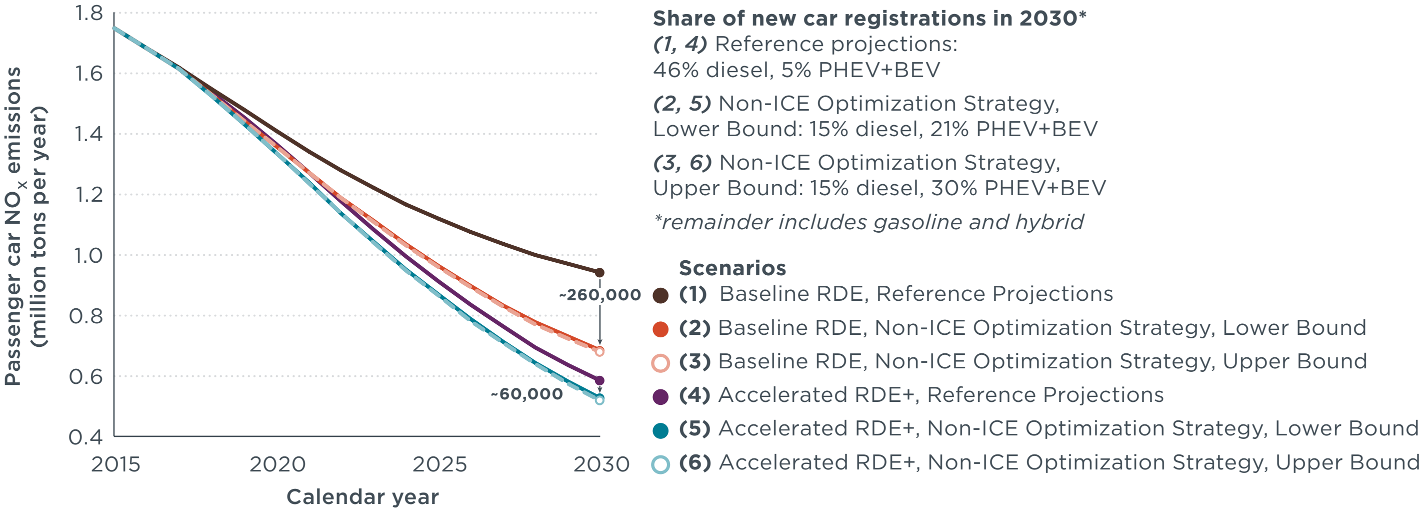

Figure ES- 3. EU passenger car fleet NO_x emissions by scenario, 2015–2030.

These findings show that CO_2 emissions from the new car fleet in Europe can be reduced even if the market share of diesel cars would continue to fall in future years. In fact, a transition from diesel cars to advanced gasoline technology and either hybrid or plug-in vehicles, including gasoline plug-in hybrid and battery electric vehicles, would reduce the net costs of complying with a hypothetical 70 g/km CO_2 standard for 2025. These reduced costs result in part from recent technological progress, including a significant reduction in battery costs. At the same time, a reduced diesel market share would reduce fleetwide real world NO_x emissions, although our results also highlight the importance of strengthening the RDE program as a primary action to reduce passenger car NO_x emissions (Miller & Franco, 2016).

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ABBREVIATIONS

BEV	Battery electric vehicle
CO	Carbon monoxide
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
EU	European Union
EV	Electric vehicle
FCV	Fuel cell vehicle
HC	Hydrocarbon
HEV	Hybrid electric vehicle
HICP	Harmonized Indexes of Consumer Prices
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
LCV	Light commercial vehicle
NEDC	New European Driving Cycle
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (nitric oxide and nitrogen dioxide)
PHEV	Plug-in hybrid electric vehicle
PC	Passenger car
PM	Particulate matter
RDE	Real-driving emissions
SUV	Sport utility vehicle
UK	United Kingdom
U.S.	United States
ZEV	Zero emission vehicles

1. INTRODUCTION

In 2015, more than half of the new cars in the European Union (EU) were diesel cars (Mock, 2016). India and South Korea are the only other major car markets with an equally large diesel share. Other car markets differ considerably. The U.S., Chinese, and Japanese light-duty vehicle markets are all dominated by gasoline-fueled cars, with the role of diesels mostly limited to light-commercial vehicles and pickups. The large diesel market share in the EU is largely a consequence of both preferential tax treatment for diesel fuel and more lax tailpipe emission standards for diesel engines relative to gasoline engines.

In assessing the carbon dioxide (CO_2) reduction potential and compliance costs of future vehicle CO_2 performance standards in the EU, the International Council on Clean Transportation (ICCT) previously has assumed a constant market share for diesel cars (Meszler, German, Mock, & Bandivadekar, 2012, 2016). This assumption was valid in previous years, as the average diesel market share fluctuated only between 50% and 55% during the years 2010–2015.

From today's perspective, however, the market share of diesel cars in Europe could decrease significantly in future years based on a combination of forces. As a result of "dieselgate," the late-2015 emissions cheating scandal, there may be a loss in trust among car buyers, wondering whether a diesel vehicle purchased today has indeed the low emission levels promised in sales brochures and whether it may still enter into the centers of European cities in future years. Several metropolitan areas, such as Paris, Madrid, and Athens, already have announced limiting access for certain vehicles and it is expected that others will follow (Harvey, 2016). In addition, some EU member states, such as France, already have changed or have plans to change their fuel tax structure, lowering the tax benefit that is granted to diesel fuel in most European countries today.

In addition, dieselgate has, on the regulatory side, led to an accelerated tightening of light-duty vehicle certification testing protocols. In particular, the European real-driving emissions (RDE) regulation, which will first come into effect in September 2017, is expected to introduce a test procedure that more reliably captures real-world emissions behavior, thereby improving the real-world emissions performance of new vehicles and significantly reducing their emission of nitrogen oxides (NO_X)[2] (Franco & Mock, 2015; Mock, 2017). These regulatory developments are likely to require the deployment of more advanced aftertreatment systems for diesel vehicles, thereby increasing engineering costs and final purchase prices for those vehicles. However, the development of cheaper and more powerful batteries for electric and hybrid cars is progressing more quickly than previously expected (Wolfram & Lutsey, 2016). The combination of all these measures may lead to a change in vehicle purchase behavior, with more customers opting against purchasing a diesel vehicle and vehicle manufacturers rethinking investment decisions. Some manufacturers already have announced the gradual phase out of diesel cars in favor of an increased deployment of electrified vehicles (Frost, 2016).

In light of these recent developments, this paper aims to assess how a decrease in diesel market share may influence the cost of compliance with CO_2 performance standards and passenger car NO_X emissions in the EU. The balance of this paper is divided into three parts. Section 2 examines the diesel market situation in the EU in general and compares it to other key automotive markets worldwide. Section 3 provides a quantitative assessment of the expected change in compliance costs for reaching a hypothetical CO_2 performance standard for new passenger cars in the EU by 2025 under an assumption of decreasing diesel market share. Section 4 provides an assessment of the change in NO_X emissions assuming the same decreases in diesel market share.

2 NO_X refers to both nitric oxide (NO) and nitrogen dioxide (NO_2). The amount of atmospheric NO versus NO_2 that originates from vehicle emissions depends on several factors, including the intensity of sunlight and local physical and chemical conditions.

2. THE PASSENGER CAR DIESEL MARKET IN THE EU

2.1 HISTORIC REASONS: WHY ARE THERE SO MANY DIESEL CARS ON EUROPEAN ROADS?

Between 1990 and 2015, the average share of diesel cars in Western Europe's new passenger car market increased from about 14% to 52%, and reached a maximum of around 56% in 2011 (Figure 2). Before 1990, diesel engines were largely limited to the commercial road transportation market, but they rapidly gained market share in the European passenger car market after that period in response to a wide range of technological, economic, political, and social factors (Berggren, Magnusson, & Sushandoyo, 2009).

Since the 1980s, the pump price of gasoline has been higher than that of diesel fuel in most Western European countries. The price differential is widely considered a key driver of European dieselization and results from the lower fuel tax imposed on diesel fuel over the past three decades (Runkel, Mahler, Schmitz, Schäfer-Stradowsky, 2015; Cames & Helmers, 2013). To date, the United Kingdom (UK) is the only Western European country that has identical gasoline and diesel fuel duties, introduced in response to a growing concern about the environmental impacts of diesel exhaust emissions (European Automobile Manufacturers Association [ACEA], 2016a; Burguillo, Jorge, & Romero, 2009; Fergusson, 2000). In 2011, the European Commission proposed a revision of the Energy Tax Directive which, among other goals, aimed to reduce the disparity between gasoline and diesel fuel taxation (European Commission, 2011). However, the proposal was withdrawn in 2014 because of a lack of consensus among the EU member states.

Diesel engines typically have featured greater fuel efficiency and lower CO_2 emissions than their gasoline counterparts, although the CO_2 benefits are substantially lower than the fuel savings because diesel fuel contains 14% more CO_2 per liter than gasoline. Governments have thus incentivized diesel cars on the basis of their expected greenhouse gas savings (Sullivan, Baker, Boyer, Hammerle, Kenney, Muniz, & Wallington, 2004; Zachariadis, 2006). At the same time, manufacturers have successfully marketed diesel as a cost-effective technology for consumers, supported by the lower diesel fuel prices (Neumaier, 2010). In the mid-1990s, the market breakthrough of two important technological developments, turbo charging and common rail direct injection, significantly improved the performance of diesel-powered cars and boosted their incipient popularity (Berggren et al., 2009).

The uptake of diesel engines was also favored by EU tailpipe emission norms for air pollutants. The Euro 2 standard, introduced in 1996, set different carbon monoxide (CO) and hydrocarbon plus NO_x ($HC + NO_x$) emission limits for gasoline and diesel cars. It allowed diesel cars to emit up to 40% more $HC + NO_x$ than gasoline models and established only a modest limit on diesel particulate matter (PM), thus deferring the need for diesel exhaust aftertreatment systems. Diesel oxidation catalysts for PM reduction were not required on EU diesel cars until the arrival of the Euro 3 standard in 2000 (Posada Sánchez, Bandivadekar, & German, 2012). And even with the current Euro 6 standard, diesel cars are allowed 33% more NO_x emissions than gasoline cars.

Historical market shares of diesel passenger cars vary significantly by EU member state, as shown in Figure 1. Examples from the Dutch, Greek, and French markets provide a useful illustration of reasons for variation in diesel market share within the EU. The Netherlands, where the diesel car market is comparatively small, has historically imposed high purchase and annual taxes on diesel cars. In the country's current CO_2-based taxation scheme, a diesel surcharge is added to both vehicle registration and ownership taxes[3] (ACEA, 2016a). New diesel cars are usually registered as company cars and are only cost-efficient with annual mileages of 20,000 km or more (Ligterink, 2014). According to Cames and Helmers (2013), Dutch diesel deterrence taxes may reflect concerns over air quality and/or the high domestic refinery output of gasoline.

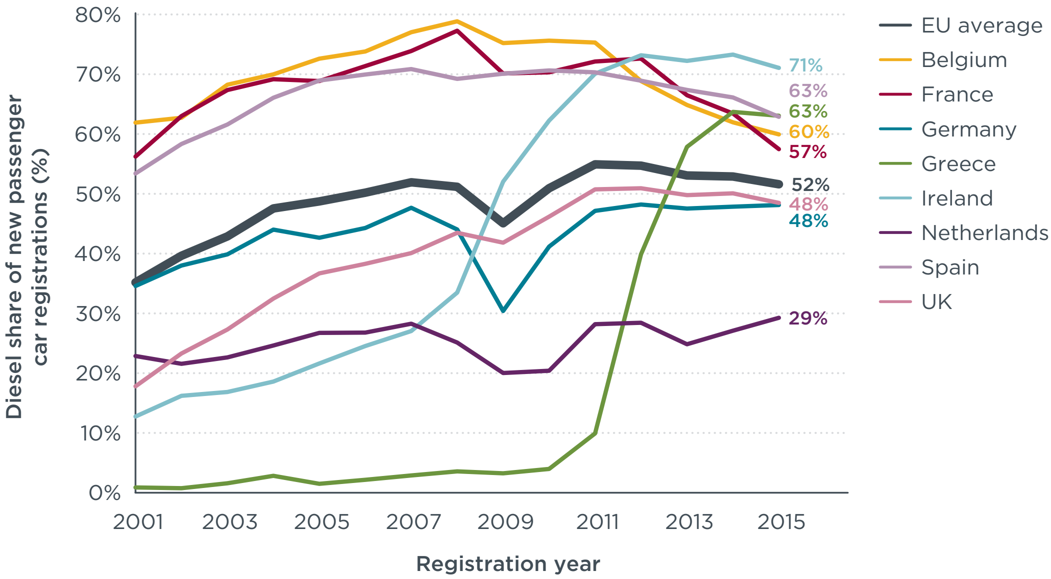

Figure 1. Market share of diesel passenger cars by member state and registration year. *Source: Mock (2016).*

In Greece, the share of diesel passenger cars did not exceed 10% until 2011. Diesel cars were banned from the major cities of Athens and Thessaloniki between 1991 and 2011 to protect ancient limestone buildings from the acid deposition effects of exhaust emissions. The government lifted the ban in 2011 on the basis of the assumed climate benefit of diesel engines (Fameli & Assimakopoulos, 2013). As a result, and considering that the national tax on diesel fuel is about half that of gasoline, new diesel registrations increased dramatically and reached a market share of about 64% within 3 years.

France was one of the first EU member states where the share of new diesel registrations surpassed that of gasoline, which happened around 2000. In the early 1980s, French car manufacturers took the lead in diesel engine development and the government introduced fiscal measures to stimulate diesel sales (Dell, Mosely, & Rand, 2014). The current CO_2-based bonus-malus (feebate) vehicle taxation system, in force since 2008, incentivizes cars with lower CO_2 emission values, and in contrast to the Dutch system, does not penalize diesel engines. The French government has, however, recently taken steps to curb diesel sales and remove older diesel cars from the road to abate associated air pollutant emissions. Measures taken include narrowing the gap between gasoline and diesel fuel prices and diesel scrappage programs (Edelstein, 2015). As a result, the share of diesel cars among new registrations declined steadily between 2012 and 2015.

3 The Dutch vehicle registration tax surcharge for diesel passenger cars was about 86 euros per gram of CO_2 above 67 g CO_2/km in 2016 (European Automobile Manufacturers Association [ACEA], 2016a). The ownership tax, which varies by province and depends on vehicle curb weight and type of powertrain, is roughly double for diesel cars compared to gasoline cars (Tax and Customs Administration, n.d.).

2.2 GLOBAL CONTEXT: WHAT IS THE ROLE OF DIESEL CARS IN THE U.S. AND JAPAN?

Although diesel cars captured between 30% and 50% of the Western European vehicle market from 2000 to 2015, their share did not exceed 5% in the United States and Japan. China, where car sales have boomed over the last decade,[4] also has not embraced diesel passenger cars. In 2010, only 2% of the Chinese passenger car fleet used diesel fuel (Wang, Fu, & Bi, 2011). However, in all three markets, diesel engines are common among light-commercial vehicles and pickups.

In the United States, during the aftermath of the oil crises of the 1970s, the share of diesel cars increased slightly and peaked at around 6% in 1981, then dipped to less than 1% by 1985 and has since remained at similarly low levels. U.S. fuel prices are among the lowest in the world and diesel fuel and gasoline taxes are relatively equal, which, combined with the price premium of diesel cars, has had a deterrent effect on diesel sales. Further, U.S. motor vehicle emissions regulation, which does not differentiate by fuel type, restricts diesel engines to producing emissions less than or equal to gasoline engines, effectively limiting the sale of diesel cars that are more costly to control (Cames & Helmers, 2013). Diesel cars also carry a negative stigma in the United States. By the turn of the century, diesel engines had earned the reputation of being "loud, sluggish, unreliable, and harmful to the environment" (Neumaier, 2010, p. 25). Although it is still too soon to judge the long-term effect of Volkswagen's October 2015 admission to using illegal defeat devices in diesel cars, the negative perception of diesel cars in the United States is expected to be even more pronounced than it previously was.

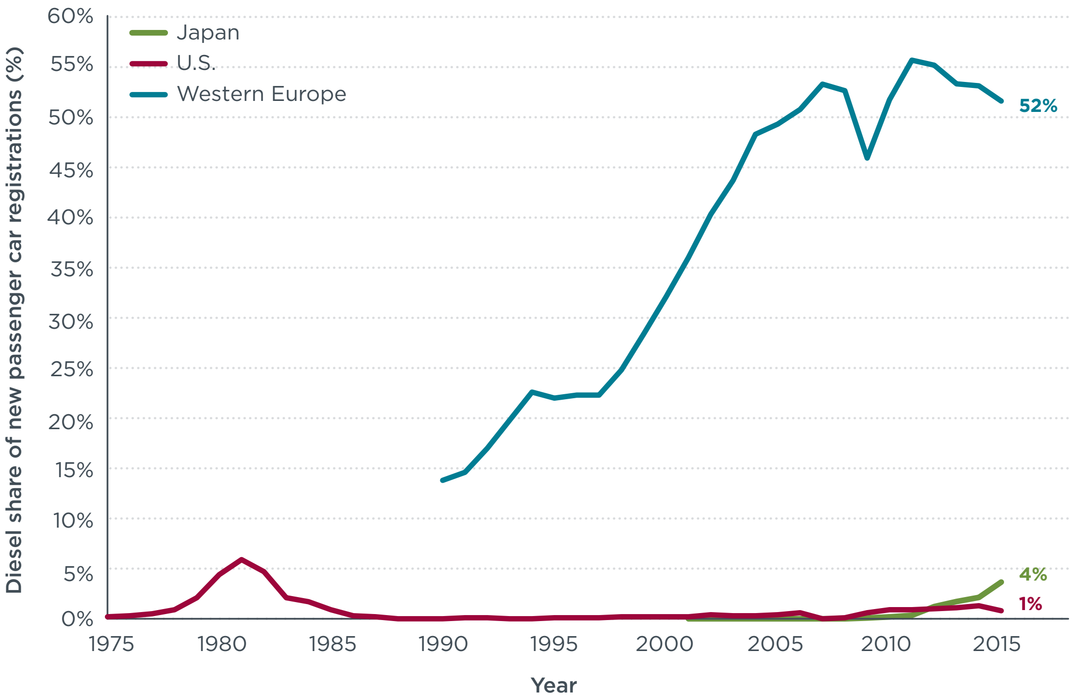

Figure 2. Market share of diesel passenger cars in Japan, the United States, and Western Europe,[5] expressed as percentage of annual new passenger car registrations. Data for Japan are available only from 2001 to 2015. *Sources: U.S. Environmental Protection Agency, 2016; European Automobile Manufacturers Association, 2016b; Japan Automobile Manufacturers Association, Inc., 2016a, 2016b; METI, 2008.*

4 In 2005, China was the fourth largest car market in terms of new registrations, behind Western Europe, the U.S., and Japan. The country became the largest market in 2011, when it surpassed the number of new registrations of Western Europe (International Organization of Motor Vehicle Manufacturers [OICA], 2016).

5 Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom, Iceland, Norway, Switzerland.

Japan's history of low diesel sales results from stringent air pollutant emissions regulation,[6] the high purchase price of diesel cars, and their reputation for being environmentally harmful and loud (MarkLines, 2012). In 1992, the central government passed in-use emissions regulations for diesel commercial trucks and buses (the *Automotive* NO_x *Law*) and subsequently expanded those requirements in 2003 to cover PM and to include light-duty diesels (Rutherford, 2006). In addition, the Tokyo Metropolitan Government passed a stringent in-use emission standard for diesel trucks and buses banning the operation of pre-1997 model year heavy-duty vehicles lacking PM control retrofits within the extended Tokyo metropolitan region starting in October 2003. Japan's vehicle taxation system levies vehicle taxation and registration fees on vehicle mass and engine displacement, thereby imposing higher costs on Japan's relatively large light-duty diesels. In addition, the country's diesel industry was slow to adopt diesel technology improvements. For example, in 2000, fewer than 20% of Japanese diesel cars had direct injection systems, whereas the share in Western Europe was around 65% (Beise & Rennings, 2005).

In 2015, 3.7% of new Japanese cars were diesel (Figure 2). This recent increase, compared to previous years where the market share was around 1%, is driven primarily by the so-called "clean diesel passenger car" technology, which is to say, diesel cars that are compliant with the current emission standards, which are equivalent to Euro 6 or U.S. Tier 2 standards (Kodjak, 2015). As part of its support of more fuel-efficient cars, Japan introduced, beginning in 2009, "eco-car" tax breaks and subsidies for clean diesel cars, among other fueling technologies (International Energy Agency, 2016).

2.3 COUNTRY LEVEL COMPARISON: IS DIESEL TECHNOLOGY A PREREQUISITE FOR REDUCING CO_2 EMISSIONS?

CO_2 emission levels of new cars in the EU, United States, and Japan have decreased in recent years, as Figure 3 clearly shows for the time period 2001–2014. The absolute CO_2 levels, in g/km, differ among the three markets, not in the least because of differences in the fleet composition. For example, the average passenger car weighs about 1,400 kg in the EU, whereas the average car in Japan is about 200 kg lighter and 200 kg heavier in the United States (Mock, 2016). Nevertheless, the reduction of CO_2 levels is evident in all three markets, and is most pronounced in Japan. Between 2001 and 2014, Japan's average CO_2 emissions for new cars decreased from 182 to 115 g CO_2/km,[7] a 37% reduction.

At the same time, the market share of diesel cars remained very low—below 5%—in the United States and Japan, and nearly constant—around 50%—in the EU between 2004 and 2014. Meanwhile, the market share of hybrid electric vehicles[8] (HEV) has increased notably in Japan, where in 2014 about 20% of new cars were equipped with this technology. In the United States, the HEV share increased to a level of 3% in 2014 and in the EU to 1.4% (Mock, 2016).

6 Japan's 2005 "new long-term emissions regulation", adopted in reaction to an anti-diesel campaign led by Tokyo Governor Shintaro Ishihara starting in 1999 (Rutherford, 2006), specifically targeted diesel cars and was the most stringent air pollutant regulation in the world at that time (Nilsson, Hillman, Rickne, & Magnusson, 2012).

7 All values given are expressed as NEDC (New European Driving Cycle) equivalent. The development of real-world CO_2 emissions is not within the scope of this report. More details on this subject can be found in Tietge, Díaz, Mock, German, Bandivadekar, & Ligterink (2016).

8 Throughout this report, the term hybrid refers to gasoline and diesel hybrid electric vehicles (HEVs), excluding plug-in hybrid electric vehicles (PHEVs).

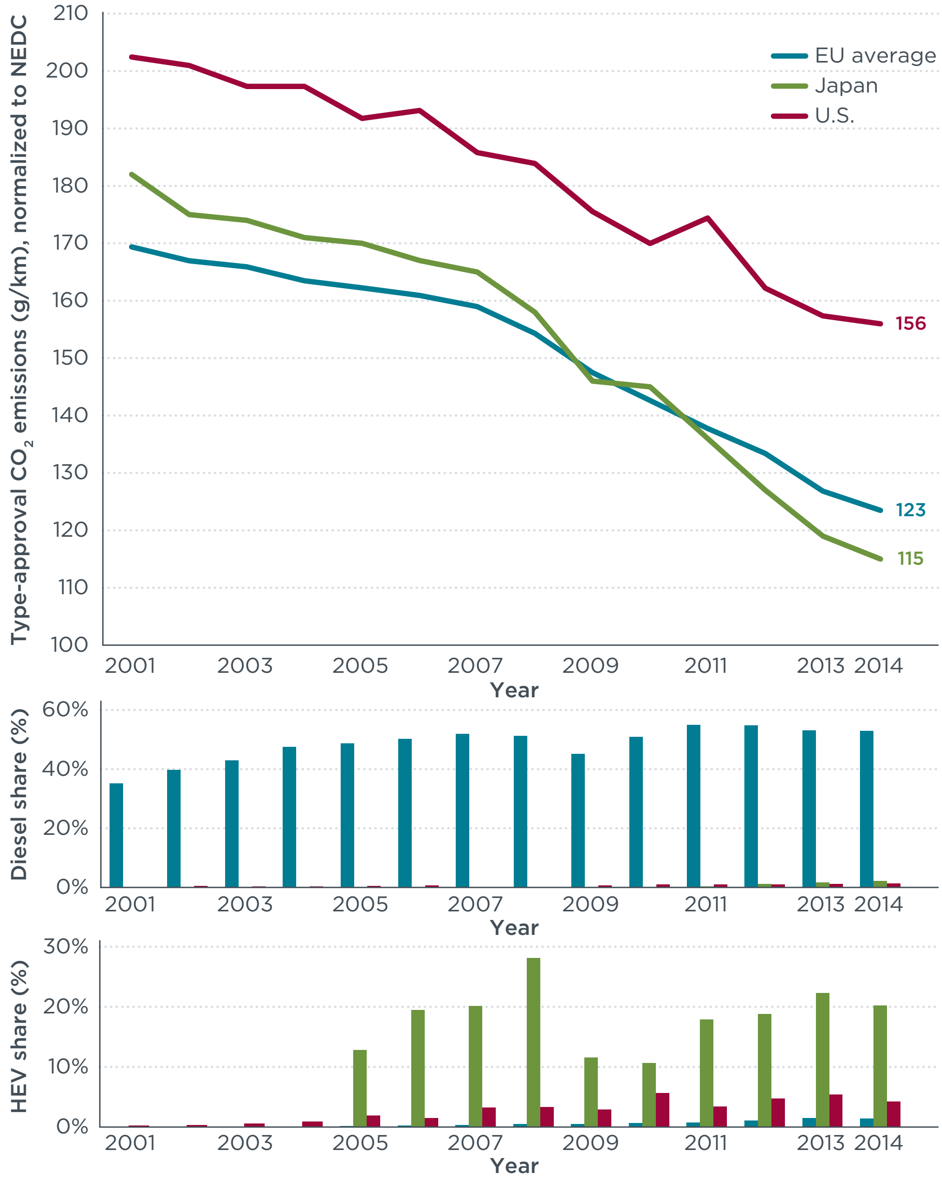

Figure 3. Average type-approval CO_2 emissions of new passengers in Japan, the United States, and the EU. The lower graphs show diesel and HEV shares, excluding PHEVs, of new passenger car registrations in those countries. *Source: Mock (2016).*

A similar observation can be made within the EU, for example when comparing the trends in CO_2 emissions and diesel/HEV market shares for France, Germany, and the Netherlands (Figure 4). Although all three countries have reduced new car CO_2 emissions over the last 15 years, the Netherlands stands out with the most pronounced decline of average emission levels. Dutch emissions declined from around 174 g CO_2/km in 2001 to about 102 g CO_2/km in 2015, the lowest value in the EU and corresponding to a 41% reduction. In comparison, the average new car in Germany in 2001 had a very similar CO_2 level to those in the Netherlands (179 versus 174 g/km), but then emissions in Germany decreased by only about 29% to an average level of 127 g/km in 2015. The average new vehicle mass increased by about 8%–9% in both countries over the same time period. In France, the average CO_2 emission level of new cars decreased, similar to Germany, by about 30% between 2001 and 2015, while in parallel the average mass of new cars increased by about 5% (Mock, 2016).

As for the international comparison, it is remarkable that the market share of diesel cars did not change significantly although the CO_2 emissions in these three EU member states decreased over time. For the Netherlands, it remained at about 25%; for Germany it increased from 35% in 2001 to 48% in 2015 but remained mostly constant at around 45% between 2004 and 2015; and in France it increased between 2001 and 2008, but then decreased again to end up at a level of 57% in 2015, which is nearly identical to the value in 2001. This observation of a relatively stable diesel market share in the 2001–2015 time frame holds true even though there were some noticeable short-term changes. For example, diesel car sales in Germany were particularly affected by the economic crisis around 2008, as consumers turned to lower priced gasoline vehicles, and the share of diesel cars hit a low point of about 30% in 2009 (Kaul, Pfeifer, & Witte, 2012).

Although the diesel market shares did not change drastically, the market share of HEVs has noticeable increased over the same time period. In the Netherlands, the share of HEVs went from zero to 5.7% in 2013 before declining again to 3.3% in 2015. In addition, the market share of plug-in hybrid electric vehicles (PHEVs) skyrocketed to 8.9% by 2015, which is not reflected in Figure 4. This is by far the highest market penetration of PHEVs of all the EU member states and well above the EU average of 0.6%, resulting from an effective national fiscal incentives program (see Tietge et al., 2016, and Yang, Slowik, Lutsey, & Searle, 2016). In France, although not as pronounced as in the Netherlands, the market share of HEVs has increased to a level of 2.2%, with 0.2% being PHEVs. In Germany, only 0.6% of all new cars in 2015 were HEVs, which included 0.3% PHEVs.

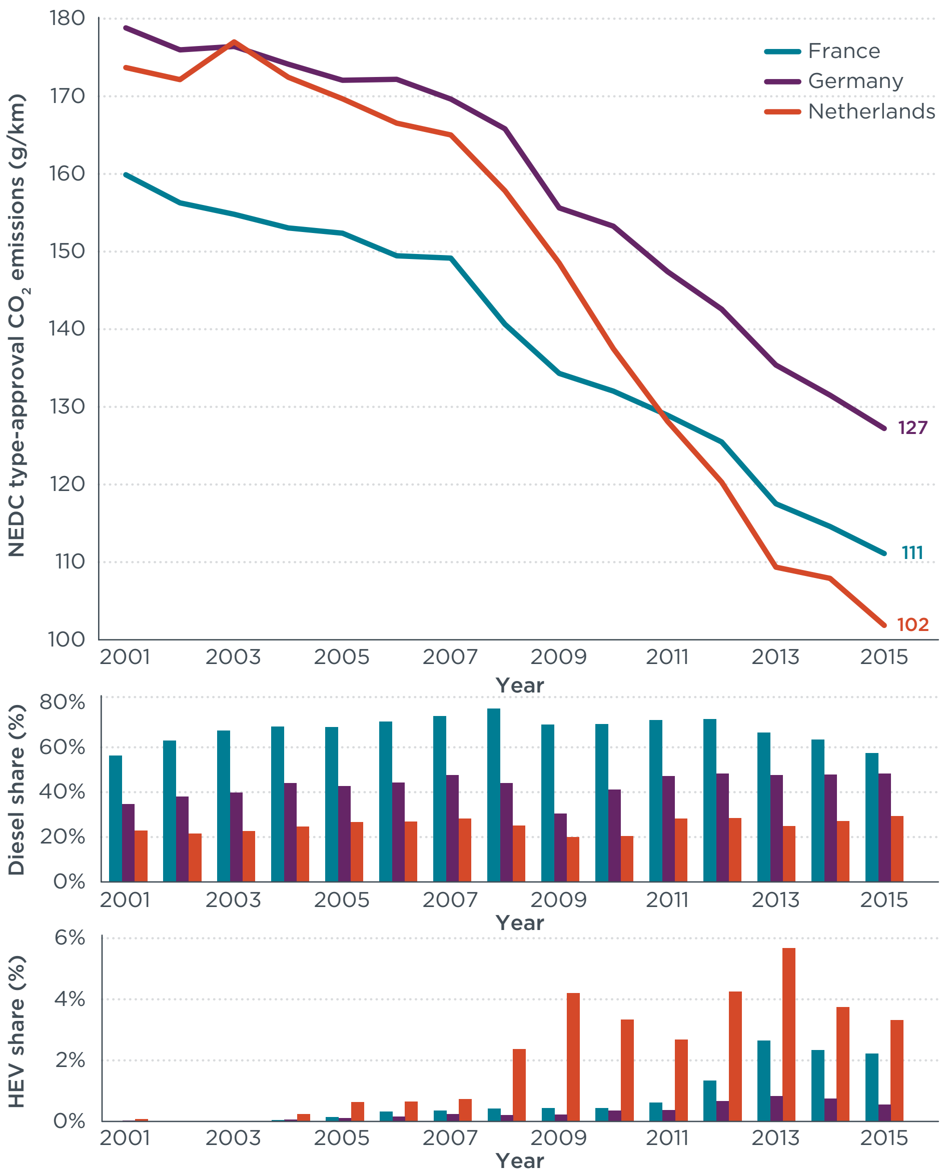

Figure 4. Average type-approval CO_2 emissions from all new passenger car registrations in France, Germany, and the Netherlands. The lower graphs show diesel and HEV shares of new passenger car registrations in those countries. *Source: Mock (2016).*

The data presented in Figure 3 and Figure 4 indicate that a high market share of diesel cars or an increase in the share of diesel cars is not necessary for cutting CO_2 emissions. Both Japan and the Netherlands have achieved substantial emission reductions with relatively low shares of diesel cars. In the case of Japan, the CO_2 emission reduction has occured while complying with stringent air pollutant emission regulations. Incremental advances in gasoline and diesel technology and an increased deployment of hybrid engine technology—both HEV and PHEV—were the major CO_2 reduction drivers in these markets.

2.4 VEHICLE SEGMENT LEVEL COMPARISON: WHAT IS THE CO_2 BENEFIT OF DIESEL CARS AND WHAT IS THE PRICE CONSUMERS PAY?

Between 2001 and 2015, average CO_2 emission levels of new cars in the EU declined from 169 to 120 g CO_2/km, equivalent to a reduction of roughly 29%. In 2001, the average CO_2 emission level of gasoline cars was still about 8% higher than that of diesel cars, but the difference between both fuel types decreased to only about 3%

in 2015 (123 versus 119 g/km), which is to say the average CO_2 level of gasoline cars decreased more quickly in 2001–2015 than it did for diesel cars, as shown in Figure 6. It should be noted, though, that at the same time, the average engine power of new diesel cars increased by about 31% to 101 kW in 2015, whereas for gasoline cars it increased by only about 14% to a level of 83 kW in 2015. Similarly, the average mass of diesel cars increased by about 9%, but gasoline vehicles gained only 2% in weight over the same time period (Mock, 2016).

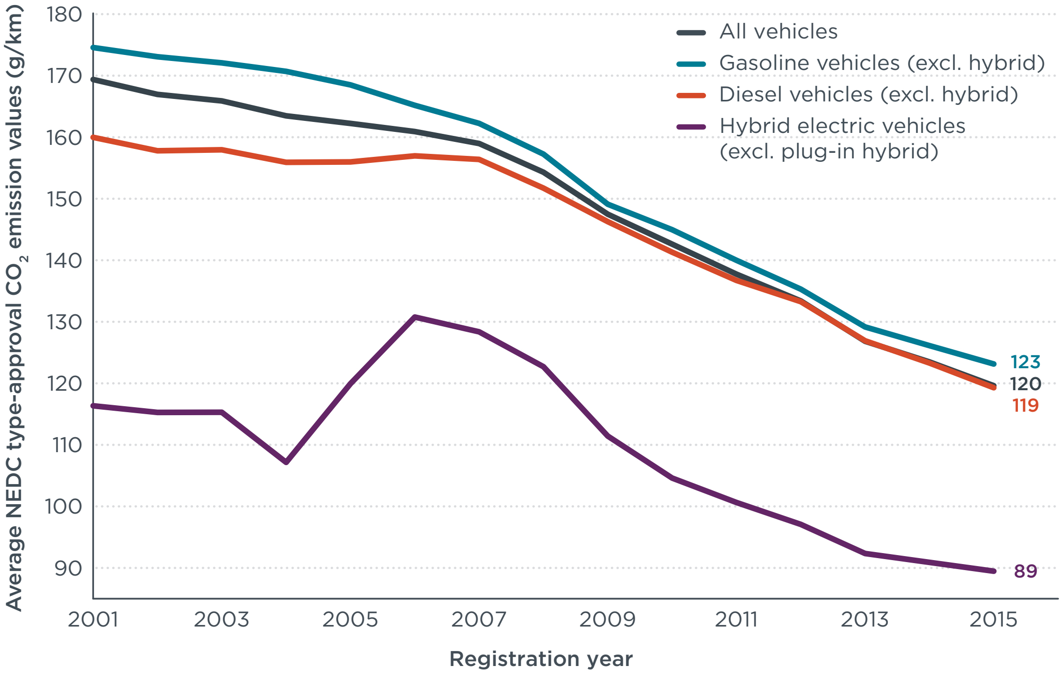

Figure 5. Sales-weighted average type-approval CO_2 emissions from new EU passenger cars by fueling technology. *Source: Mock (2016).*

For a more robust comparison, the analysis focuses on one specific vehicle segment and looks at diesel and gasoline vehicles within this segment. Figure 6 shows the distribution of diesel market shares by vehicle segment for the EU average. In the upper medium and medium segments, diesel cars made up about 87% and 82% of 2015 sales, respectively. Diesel is also still the preferred option in the luxury and sport utility vehicle (SUV) segments, but it has notably lost market share in both since 2012. The share of diesel cars in the small segment decreased from around 36% to 25% between 2011 and 2015 and remained negligible for the mini car segment in recent years. In the lower medium segment, diesel cars account for just over half the sales. The lower medium segment therefore features the most balanced market shares of gasoline and diesel cars and also captures the highest volume of HEV sales (roughly 102,000 units, accounting for about 46% of total HEV sales in 2015). Furthermore, the lower medium segment is the segment with the highest market share overall of 30%. With these figures in mind, the lower segment is selected for further analysis.

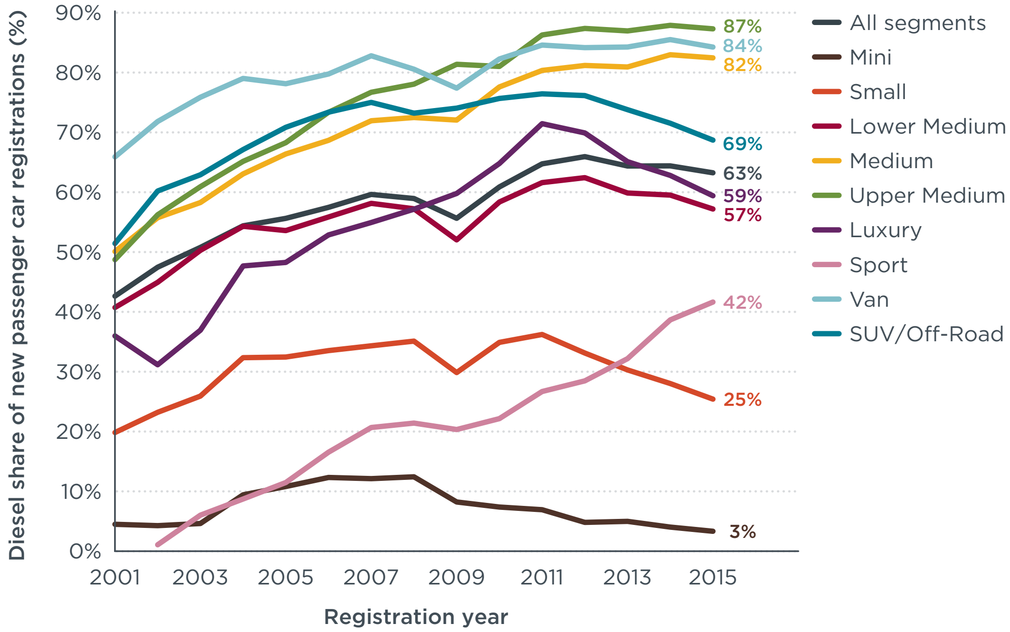

Figure 6. Market share of new EU diesel passenger cars by segment. *Source: Mock (2016).*

Figure 7 depicts the trend of CO_2 emissions by fueling type for the lower medium segment and shows that, within the segment, diesel cars emit less CO_2 than gasoline cars. Between 2001 and 2015, the CO_2 advantage of diesel cars remained rather constant at around 17%, whereas the absolute difference between both fuel types decreased from 29 to 21 g CO_2/km. HEVs feature by far the lowest CO_2 emissions of the three fueling types. In 2015, average CO_2 emissions from hybrid cars were about 32% and 18% below the gasoline and diesel average values, respectively. However, CO_2 emissions from HEVs declined at a slightly lower rate than those from conventional engines. Between 2010 and 2015, the CO_2 advantage of hybrid cars dropped from about 40% to 32%, compared to the gasoline baseline. The share of HEVs in the lower medium segment increased gradually in recent years, but hybrids still accounted for less than 2.5% of segment sales in 2015.

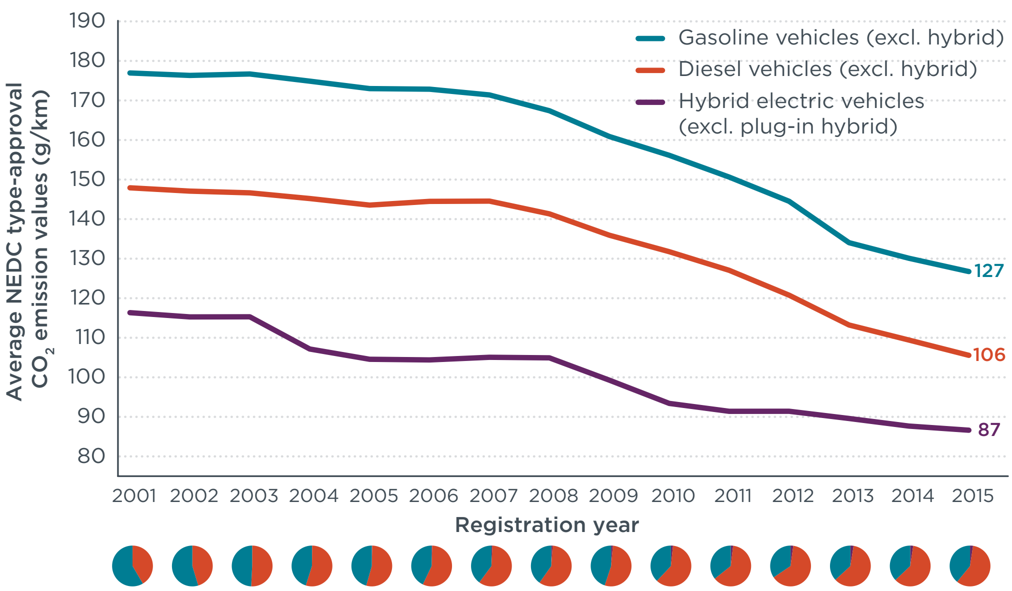

Figure 7. Sales-weighted average type-approval CO_2 emissions from EU lower medium passenger cars by fueling technology. Pie charts present the market share of gasoline, diesel and hybrid vehicles in each year. *Source: Mock (2016).*

Retail prices of vehicles might vary significantly between countries because of differences in registration taxes, socioeconomic factors, or differences in manufacturers' national pricing strategies, among others. Thus, the analysis of retail prices is carried out for one specific country, in order to avoid distortions caused by variations in national taxation systems during the study period. Germany was selected as a market for the comparison because it is the largest vehicle market in the EU. Further, vehicle taxes in Germany have remained fairly stable during the studied time frame.

Figure 8 and Figure 9 show the trend in average retail prices for lower medium passenger cars by fueling type in the German market between 2001 and 2015. Figure 8 presents the absolute price values and Figure 9 shows price averages for diesel and hybrid cars, expressed as a percentage of gasoline car prices. Prices include taxes and are adjusted for inflation to 2016 euros using German Harmonized Indexes of Consumer Prices (HICP) based on Inflation.eu (2017).

In Germany, average retail prices from lower medium gasoline and diesel cars increased only slightly over the analysis period, except in the wake of the financial crisis in 2009 when the average gasoline car price dropped to a record low of 22,838 euros (2016 euros). Overall, from 2001 to 2015, gasoline and diesel car prices increased by around 9% and 10%, respectively. During this period, the price premium for diesel cars ranged from 10% to 23%, with an average of about 16%. In 2009, the difference between both fuel types peaked at 23% but fell gradually to 13% in 2015, around two percentage points higher than in 2001.

Average retail prices of lower medium HEVs declined by approximately 6% from 2001 to 2015. Although in 2001 hybrid cars were priced about 23% higher than gasoline cars, the price premium decreased to roughly 6% in 2015. Between 2013 and 2015, hybrid cars were, on average, cheaper than diesel cars. In 2015, the average price of hybrid cars was about 6% lower than the diesel average.[9]

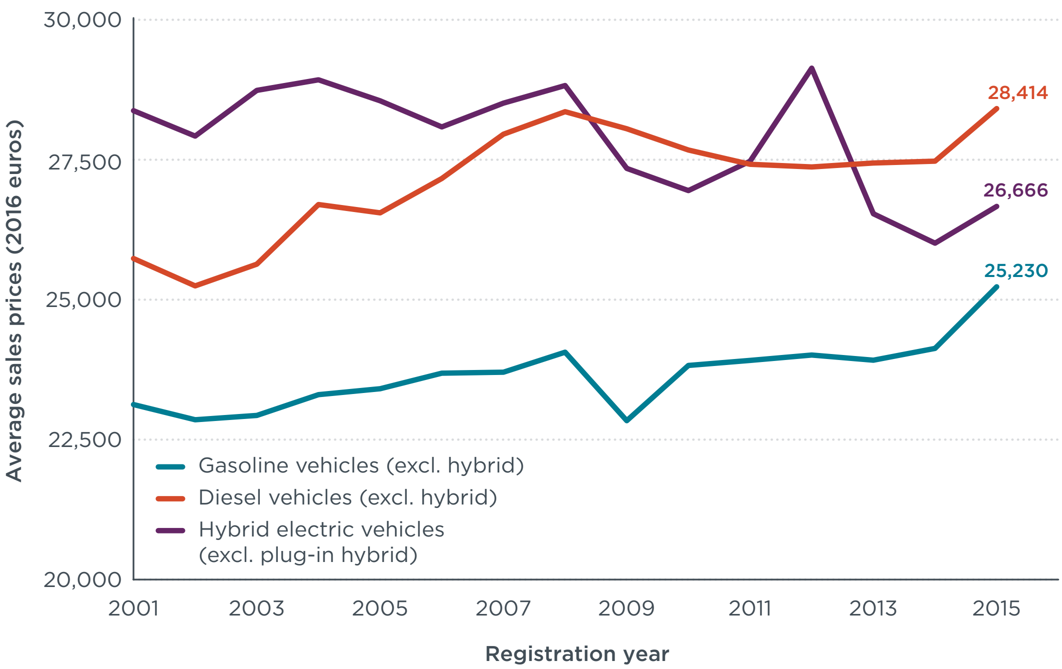

Figure 8. Sales-weighted average sales prices, in 2016 euros, from new lower medium passenger car registrations in Germany, by fueling technology. *Source: Mock (2016).*

9 Between 2001 and 2015, the German hybrid market was largely dominated by two models, namely the Toyota Prius and the Toyota Auris. The Toyota Prius accounted for an average share of around 74% of lower medium hybrid sales from 2001 to 2010, after which it started losing market share to the Auris. In 2015, Auris sales captured about 79% of the lower medium hybrid market.

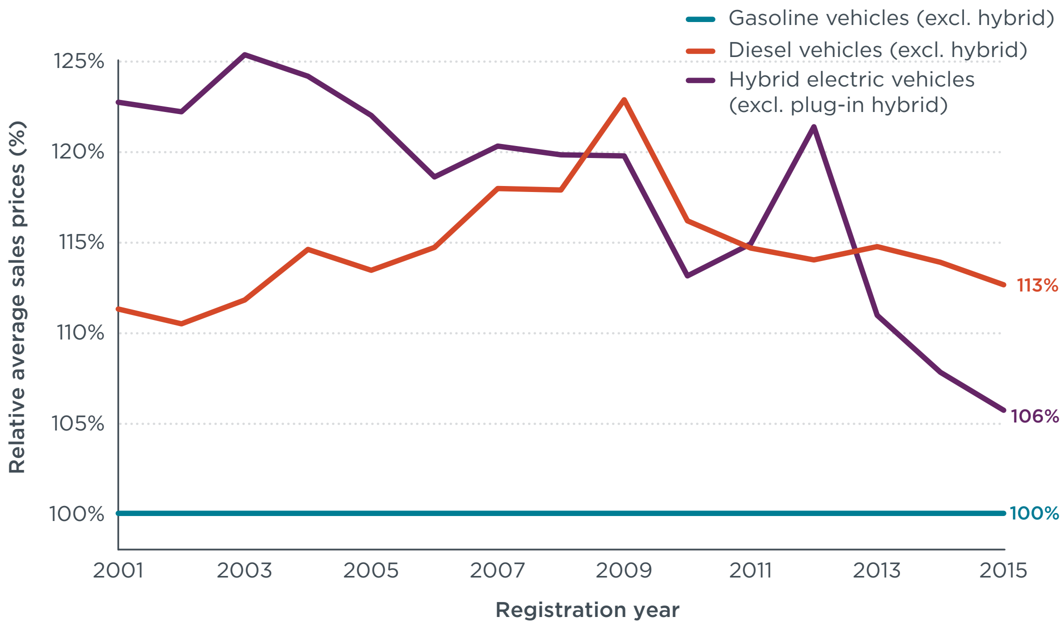

Figure 9. Sales-weighted average sales price (2016 euros) from new lower medium passenger cars registered in Germany, by fueling technology, expressed as a percentage of gasoline vehicles average sales prices. *Source: Mock (2016).*

Figure 10 brings together the CO_2 reduction and vehicle price increase. It takes the average retail price difference between lower medium segment diesel and HEV cars, compared to gasoline cars of the same segment, and puts that retail price difference into perspective to the average difference in CO_2 emission levels between diesel and HEV cars, again compared to their gasoline car counterparts. The result is the price increase per g/km of CO_2 reduced when moving from an average gasoline car to a diesel or HEV car.

According to this metric, in 2001, purchasing a diesel car or HEV instead of a gasoline car would have resulted in a purchase price premium of about 90 euros per gram of CO_2 saved. Between 2003 and 2015, the price premium of cutting average CO_2 emissions using conventional diesel engines increased, while that of hybrid cars declined. In 2015, buying a hybrid or diesel car instead of a gasoline car translated to a purchase price premium of around 35 euros for hybrids and about 169 euros for diesels per gram of CO_2 saved.

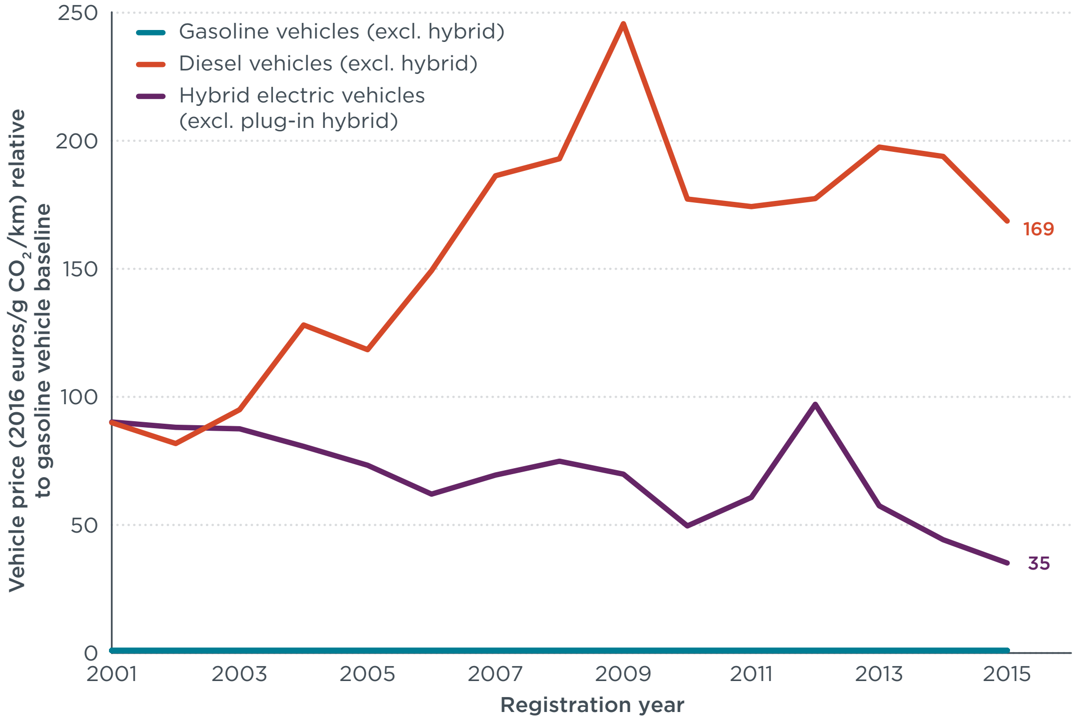

Figure 10. Sales-weighted average increase in vehicle sales price per g CO_2/km mitigated from new diesel and hybrid lower medium passenger cars registered in Germany, relative to the average gasoline passenger car. *Source: Mock (2016).*

It is clear that the price of a vehicle only allows for a meaningful comparison between vehicles and between powertrains to a limited extent, as the price is influenced not only by the production cost of the vehicle but also by marketing measures of the vehicle manufacturer and dealer.[10] Nevertheless, given that vehicle production costs are generally not publicly accessible although vehicle prices are, the analysis underlying Figure 10 indicates that when switching from gasoline to HEV, the average price increase per g/km of CO_2 avoided has declined significantly in recent years, thereby providing a more efficient way of reducing CO_2 than switching from gasoline to diesel cars.

10 For example, variations in trim level choice and standard equipment by fueling technology have a large impact on the retail price. HEV models typically come with more comprehensive standard equipment than conventional engines (German, 2015). On the other hand, manufacturers might decide to cross-subsidize certain products. For example, according to Dijk & Yarime (2010), Toyota initially cross-subsidized around 10% of each Prius sold in the United States as it was launched in 1997.

3. INFLUENCE OF DIESEL MARKET SHARE ON FUTURE CO_2 PERFORMANCE STANDARDS

The ICCT has previously published a series of cost curves describing the cost of CO_2 reduction technology as applied to the European passenger car fleet in the 2025-2030 time frame (Mezler et al., 2016). These curves allow for the determination of the per-vehicle costs of complying with various CO_2 emission standard levels using different technologies. An underlying element of the previous ICCT cost curve study is an assumption that the makeup of the European passenger car fleet does not change over time, so that vehicle class distributions and gasoline and diesel market shares are held constant throughout the evaluation period. Given the relatively large market share of diesel vehicles in the European passenger car market and the potential for changes in that share in response to changes in consumer preference and increasing regulatory pressure, a key factor of interest is how diesel market share changes might affect CO_2 investment costs. To quantify this sensitivity, the ICCT cost curve analysis was replicated under a series of alternative diesel market share scenarios to evaluate associated changes in the cost of compliance for a hypothetical 70 g/km CO_2 emission standard, as measured over the New European Driving Cycle (NEDC).

3.1 BACKGROUND: COST CURVE RESULTS ASSUMING A CONSTANT DIESEL MARKET SHARE

The ICCT cost curves are developed primarily from data compiled through detailed vehicle simulation modeling and bottom-up cost estimation work performed for the ICCT by FEV, Inc. (2015). Such data are combined with supplemental data as needed, as documented in Mezler et al. (2016) to generate CO_2 cost curves for 10 EU vehicle classes, namely, diesel B, C, D, E, SUV, and LCV classes and gasoline B, C, D, and E classes. Individual class curves are sales weighted to estimate fleet average compliance costs.

FEV's simulation modeling data focused primarily on conventional internal combustion engine (ICE) powertrain technology, including onboard-only charged HEV systems. Electric vehicle technology with lower CO_2 emissions can also play a role in achieving stringent CO_2 emissions targets. Electric vehicles (EVs) as defined for this study include pure (i.e., no ICE) battery electric vehicles (BEVs), off-board charging-capable (or plug-in) hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles (FCVs).[11] Cost estimates for electric vehicles were taken from a recently released ICCT study on the cost of such technology in Europe in the 2020–2030 time frame (Wolfram & Lutsey, 2016).

CO_2 compliance costs were evaluated under two sets of assumptions, one reflective of lower bound compliance costs and one reflective of corresponding upper bound costs. Both are based on the same fundamental data, but differ in the following assumptions:

» Mass reduction costs are included in both lower and upper bound compliance cost estimates, but upper bound estimates assume that no level of mass reduction can be achieved at less than zero cost whereas lower bound costs directly reflect lightweighting tear-down cost assessments that found modest amounts of weight reduction can be achieved while also reducing cost.

» The lower bound estimates include both test flexibility exploitation and performance-based CO_2 adjustments; upper bound estimates include neither. Test

11 Readers referencing the ICCT's previous (constant diesel market share) cost curve report should note that such vehicles were defined as "non-ICE" vehicles in that study. Thus, the term "electric vehicle" in this study is synonymous with "non-ICE vehicle" in the previous study.

flexibility adjustments capture the CO_2 benefit available to vehicle manufacturers through nuances in vehicle testing procedures. Performance-based CO_2 adjustments are designed to capture engine downsizing benefits not explicitly reflected in the simulation modeling data.

» The lower bound estimates include cost adjustments based on technology co-benefits; upper bound estimates do not. Fundamental technology cost estimates assign 100% of the cost of technology to CO_2 reduction. However, there are both co-benefits and other market drivers for many CO_2 reduction technologies. Such co-benefits include improved performance, reduced noise, improved handling, improved braking, enhanced safety, and increased durability. Lower bound cost estimates adjust the technology cost of CO_2 reduction by assigning a portion of total technology cost to applicable technology co-benefits. Upper bound estimates assign the full technology cost to CO_2 alone.

» Lower bound estimates include off-cycle technology credits; upper bound estimates do not. Off-cycle credits are available to vehicle manufacturers for technologies with CO_2 reduction impacts that are not captured through standardized regulatory testing procedures.

» Lower bound cost estimates for electric vehicles are based exclusively on ICCT estimates; upper bound estimates substitute the generally higher U.S. National Research Council (2013) battery cost assumptions.

CO_2 compliance cost estimation consists of the integration of two independent components; one reflects the level of CO_2 reduction that can be achieved through the introduction of progressively more effective ICE technology and the other reflects the CO_2 reduction that can be achieved by increasing the market penetration of electric vehicles. The cost of ICE technology is generally reflected as an upwardly sloping exponential curve. The cost of increasing electric vehicle market penetration is a linear function that serves to extend the ICE technology cost curve to lower levels of CO_2.

Although this generalization always holds true, there is a degree of freedom associated with introducing electric vehicles into the fleet that creates uncertainty with regard to the precise integration of ICE and electric vehicle cost data. There is no requirement that a vehicle manufacturer exhaust all ICE technology before introducing electric vehicles into the fleet. The cost curve analysis resolves this uncertainty by evaluating the integration of electric vehicles under two scenarios. Under one scenario, referred to as the ICE exhaustion, or ExhICE, strategy, the transition to electric vehicle technology is assumed to take place only after all ICE technology has been exhausted, as there may be barriers to introduction that are not reflected in vehicle production costs.[12] Under the second scenario, referred to as the EV optimization strategy, the transition to electric vehicles is assumed to take place at the point of cost optimization, which is to say, when the marginal cost of electric vehicles is less than the marginal cost of additional ICE technology.

The fact that the marginal cost of electric vehicles can be lower than the marginal cost of additional ICE technology does not imply that electric vehicles are less expensive than the alternative ICE technology, but rather that the cost per unit CO_2 reduction is lower. BEVs are treated as zero CO_2 vehicles in the cost curve analysis, so they provide substantial CO_2 reductions over which to spread costs. Although PHEV CO_2

12 Technology exhaustion as defined herein refers only to technology as reflected in the simulation modeling data used in the ICCT cost curve analysis. Continuing advancements, in addition to more expensive technologies not included in the simulation modeling work, will push the level of CO_2 reduction available through ICE technology to progressively lower levels than are modeled in this report. Because the cost curve analysis does not attempt to quantify these advancements, the maximum technology packages included in the simulation modeling data represent an ICE technology constraint only in the context of the ICCT cost curve analysis.

emissions are non-zero, they still provide significant reductions of more than 50%. Electric vehicle reductions are such that they can carry a cost-effective CO_2 reduction signal even while per-vehicle absolute costs are high. Because electric vehicles enter the market starting from a zero market share, fleetwide incremental cost impacts are initially modest because only a small fraction of vehicles are affected. It is this relatively small fractional cost that can be more cost effective than transitioning an entire fleet to more expensive ICE technology.

It is important to recognize that the focus on vehicle technology costs for both ICE and electric vehicles employed in the cost curve analysis does not equate to a full assessment of consumer impacts. The cost curve analysis focuses on vehicle purchase price impacts only. Impacts on the total cost of ownership for both ICE and electric vehicles would include offsetting savings as a result of reduced fuel use for ICE vehicles and alternative energy economics for electric vehicles. Such life-cycle cost assessments can be developed from the cost curve data, but are not included in the data presented in this or the earlier ICCT cost curve paper.

Figure 11 presents the derived passenger car fleet average compliance cost curves for CO_2 targets measured over the NEDC in 2025, as developed in the earlier ICCT cost curve study. Figure 11a presents compliance costs for the ICE technology exhaustion scenario and Figure 11b presents costs for the least cost electric vehicle optimization strategy. Both figures also depict the market penetration of electric vehicles required for each potential CO_2 target. As indicated, passenger vehicle NEDC standards as low as 60–70 g/km can be achieved based on limited market penetration, with a passenger vehicle NEDC standard of 70 g/km requiring an investment of 1,000 to 2,150 euros per vehicle, in 2014 euros, with no (lower bound) or very modest (upper bound) electric vehicle market penetration. Costs would be 300 to 400 euros per vehicle, in 2014 euros, lower under an electric vehicle optimized transition strategy. These are the baseline costs against which the compliance costs for alternative diesel market shares are compared.

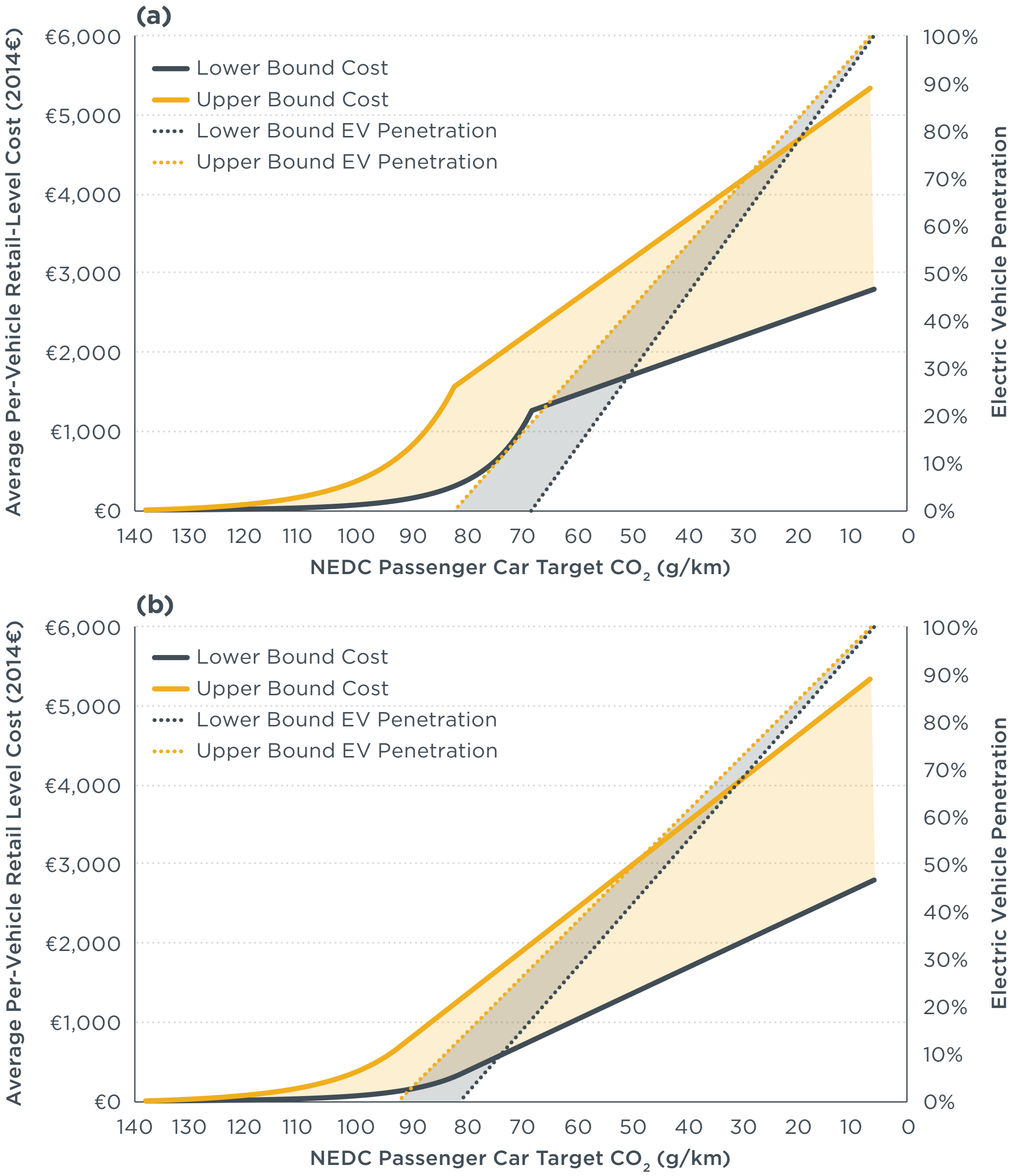

Figure 11. 2025 NEDC CO_2 costs for passenger vehicles for (a) ExhICE strategy, and (b) EV optimization strategy.

3.2 METHODOLOGY: HOW TO ACCOUNT FOR A DECREASING MARKET SHARE IN THE COST CURVES

All cost estimation for this paper is presented in terms of the differential cost of attaining a hypothetical 70 g/km fleet average passenger car CO_2 standard in 2025, as measured over the NEDC. The basic methodology used to analyze the effect of changing diesel market share impacts on the cost of CO_2 compliance was to reconstruct the EU cost curves for different powertrain shares. Although both gasoline- and diesel-specific cost curves were available by vehicle class from the original cost curve study, this is not sufficient to determine the effects of changing powertrain market shares because the level of technology required to attain a given fleet average CO_2 target changes in all classes for a shift in the market share of any individual class. Thus, cost curves across all vehicle classes must be evaluated at a revised level of CO_2 emissions in response to each market share change to maintain a constant fleet average emissions level.[13]

For this paper, this revised level of CO_2 performance is spread consistently across all vehicle classes. It is not assumed that manufacturers will preferentially implement technology in one class or another, but rather spread technology demands across classes so that class-specific emission reductions are consistent.[14] In other words, the level of technology, and thus compliance cost, required in any one class for a given fleet average CO_2 target will vary with changing class-specific market shares. Because diesel vehicles generally offer lower CO_2 emissions than their gasoline counterparts, reducing diesel market share generally means adopting more technology in gasoline vehicle classes, including more hybrid systems, or adopting greater electric vehicle market shares if insufficient or only cost-ineffective ICE technology is available to meet the target CO_2 emissions level.

The passenger car diesel market share for the baseline EU cost curve development was 56.5%, with individual class shares as depicted in Table 1.[15] For this paper, that market share was first reduced to 50% and then subsequently reduced in increments of 5 percentage points to a minimum market share of 15%. It was assumed that manufacturers would preferentially reduce diesel market share in the lightest segments first, starting with B class vehicles and progressing through C, D, and E class vehicles, so that the only diesel vehicles remaining in the 15% market share scenario were SUVs. In each market share transition, the reduced diesel market share was allocated to the corresponding gasoline vehicle class. For example, when market share is reduced for diesel B class vehicles, the market share of gasoline B class vehicles is increased by an identical amount (and the same holds for class C, D, and E vehicle market shares). Table 2 summarizes the changing diesel market shares for each of the evaluated scenarios. For each scenario, a full set of class-specific cost curves was developed.

When market shares are held constant, as in the baseline EU cost curve study, changes in CO_2 technology can generally be evaluated independent of the underlying cost differentials between baseline gasoline and diesel engines. However, when market shares

13 Take, for example, a two-class fleet with a 50/50 market share and class 1 emitting CO_2 at 90 g/km while class 2 emits CO_2 at 130 g/km for a fleet average CO_2 emission rate of 110 g/km. If the market share of class 1 vehicles is reduced to 25%, the class average CO_2 emission rate for class 2 must decline to 116.7 g/km to maintain fleet average CO_2 emissions of 110 g/km. In short, the effects of a market share change in any one vehicle class filters through to affect the cost of compliance with a given standard in all vehicle classes.

14 Emission reductions are not numerically identical on a percentage change basis across classes because emission reduction potential across classes is not numerically identical. Reductions are implemented on an identical percentage of total potential reduction basis, so that each class is assigned technology to attain X% of its maximum reduction potential, where X is determined by the target fleet average CO_2 target. This imposes equivalent reduction stringency across all vehicle classes–as opposed to identical percentage reductions–so that each class adopts an appropriate level of CO_2 reduction technology toward the attainment of a specified fleet average CO_2 target.

15 Light-commercial vehicles with a 100% diesel market share were also included in the baseline EU cost curve study, but such vehicles are not addressed in this paper. This paper focuses solely on EU passenger cars.

are shifted from diesel to gasoline, or vice versa, changes in the cost of the fundamental underlying engine technology must also be considered to derive an accurate assessment of an overall change in compliance costs. Generally, the production costs of diesel engines are greater than their gasoline counterparts. Throughout this report we refer to this as the "diesel engine premium." Manufacturers may accrue some level of cost savings under a fundamental shift in engine technology from diesel to gasoline. Such savings can be quantified and combined with any CO_2 technology cost changes to derive the net cost impact of diesel market share shifts. In this study, we present compliance costs inclusive and exclusive of the diesel engine premium to reflect the impact of these assumed savings on net compliance costs.

The cost estimation data from FEV (2015) that serve as the primary reference for both the baseline EU and this cost curve study include 2014 direct manufacturing cost estimates for baseline diesel and gasoline engines, including exhaust gas recirculation (EGR) and aftertreatment, and transmission technology. These estimates serve as the basis for determining diesel engine premiums for this analysis.[16] For this paper, baseline transmission cost differentials were ignored under the assumption that such differences were based on consumer choice influences rather than fundamental diesel and gasoline engine influences. In other words, if diesel and gasoline vehicles of the same class assume baseline M6 and M5 transmissions respectively, we assume the differential is reflective of consumer choice and not an inherent element of diesel and gasoline design.

Although basic engine cost premiums are available from the FEV data, some adjustment is required to place these costs on an equivalent footing with other technology costs. Specifically, two adjustments are necessary. First, because all cost analysis is performed for a 2025 evaluation year, 2014 cost premiums must be forecast through 2025. Second, because CO_2 reduction technology costs are expressed as retail level (i.e., consumer) costs, not direct manufacturing costs (i.e., costs to vehicle manufacturers), indirect cost estimates must be applied to the FEV engine cost estimates to derive equivalent retail level cost estimates. The basic methodology used to implement these adjustments is to apply learning factors to 2014 direct manufacturing costs to estimate equivalent 2025 costs, and to apply indirect cost markups to convert direct manufacturing costs to equivalent retail level costs. This same methodology was employed in the baseline EU cost curve analysis and a detailed discussion of the approach, data sources, and associated assumptions is included in the baseline EU cost curve report (Mezler et al., 2016). For basic engine technology costs required for this analysis, but not for the baseline constant market share cost curve analysis, an identical approach was employed with the following specific assumptions: (1) Engine costs were evaluated under an assumption of no cost reduction from a 2014 baseline cost as a result of learning, but EGR technology was assumed to decline over time from a 2014 baseline cost by 3% per year in 2015 and 2016, and 2% per year in 2017 through 2025. (2) Indirect costs for engine technology were assumed to adhere to the U.S. Environmental Protection Agency's (EPA) low complexity, long-term markups, but those for EGR technology were assumed to adhere to EPA's medium complexity, near-term markups through 2024 and long-term markups for 2025 (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration, 2012). Such learning and indirect cost assessments are fully consistent with the approaches employed in the baseline EU cost curve study.

16 It is important to recognize that this analysis focuses solely on CO_2 compliance costs and that the FEV engine cost data, as used in this analysis, are based on the costs required to achieve target CO_2 levels as measured over the NEDC. Costs associated with other potential future requirements such as RDE standards are not considered. To the extent that compliance costs for such programs might affect diesel vehicles disproportionately (e.g., by requiring more expensive aftertreatment improvements than would be required for gasoline vehicles), potential diesel engine premiums in 2025, as estimated for this analysis, may be substantially understated. We view this as appropriate for an analysis focused on CO_2, but caution that the reported cost savings estimated for a potential shift from diesel to gasoline engine technology may be conservatively low.

Finally, as described in Section 3.2, the lower bound cost estimates prepared for the baseline EU cost curve study apportion total technology cost between CO_2 reduction and associated co-benefits, mainly performance increases, if any. In keeping with that approach, diesel engine technology cost differentials are assumed to carry a 10% performance co-benefit, so that incremental diesel engine costs are discounted by 10% for lower bound cost estimation only. This co-benefit discount reduces the savings associated with transitioning from diesel to gasoline engines, again, for lower bound cost estimation only.

Table 1. Baseline passenger car market shares

Vehicle class	Gasoline market share	Diesel market share
B	25.0%	7.0%
C	17.5%	24.5%
D	1.0%	7.0%
E	0.0%	3.0%
SUV	0.0%	15.0%
Total	**43.5%**	**56.5%**

Table 2. Passenger car market share scenarios

<table>
<tr><th rowspan="2">Scenario</th><th colspan="6">Diesel market share</th></tr>
<tr><th>Total</th><th>Class B</th><th>Class C</th><th>Class D</th><th>Class E</th><th>SUV Class</th></tr>
<tr><td>1</td><td>56.5%</td><td>7.0%</td><td rowspan="2">24.5%</td><td rowspan="7">7.0%</td><td rowspan="8">3.0%</td><td rowspan="9">15.0%</td></tr>
<tr><td>2</td><td>50.0%</td><td>0.5%</td></tr>
<tr><td>3</td><td>45.0%</td><td rowspan="7">0.0%</td><td>20.0%</td></tr>
<tr><td>4</td><td>40.0%</td><td>15.0%</td></tr>
<tr><td>5</td><td>35.0%</td><td>10.0%</td></tr>
<tr><td>6</td><td>30.0%</td><td>5.0%</td></tr>
<tr><td>7</td><td>25.0%</td><td rowspan="3">0.0%</td></tr>
<tr><td>8</td><td>20.0%</td><td>2.0%</td></tr>
<tr><td>9</td><td>15.0%</td><td>0.0%</td><td>0.0%</td></tr>
</table>

3.3 RESULTS AND CONCLUSIONS: 2025 COST CURVE, ASSUMING A DECREASING DIESEL MARKET SHARE

Table 3 presents the change in CO_2 compliance costs for each of the evaluated diesel market share scenarios, as well as the market share of electric vehicles required to attain the evaluated 70 g/km NEDC standard. Also included are the savings associated with transitioning from baseline diesel to baseline gasoline engines and the resulting net cost differentials (i.e., CO_2 technology cost minus diesel engine cost savings). As discussed in the previous section, these cost savings are based on the differential between engine, EGR, and aftertreatment technology costs for diesel and gasoline engines. Table 3a depicts costs for an ICE technology exhaustion compliance strategy and Table 3b depicts CO_2 technology cost functions, exclusive of engine cost savings, and associated electric market penetration functions as the diesel market share transitions through the various vehicle classes. Figure 12 graphically presents the CO_2 technology cost functions and associated electric vehicle market penetration functions as the diesel market share transitions through the various vehicle classes.

Table 3. Retail 2025 compliance costs, in 2014 euros, for various passenger car diesel market shares under an NEDC 70 g/km standard and (a) an ICE technology exhaustion strategy, and (b) an EV optimization strategy

(a) ICE technology exhaustion strategy

Diesel market share	Per-vehicle compliance costs		Change in compliance costs from baseline		Electric vehicle market share	
	Lower bound compliance costs	Upper bound compliance costs	Lower bound compliance costs	Upper bound compliance costs	Lower bound compliance costs	Upper bound compliance costs
Exclusive of savings related to the elimination of baseline diesel engine cost premiums						
Base (56.5%)	1,012	2,173	0	0	0.0%	15.9%
50%	1,076	2,226	64	53	0.0%	15.9%
45%	1,148	2,274	136	101	0.0%	16.2%
40%	1,226	2,321	214	148	0.0%	16.5%
35%	1,305	2,369	293	196	0.0%	16.8%
30%	1,388	2,416	376	243	0.0%	17.1%
25%	1,473	2,463	461	290	0.0%	17.4%
20%	1,537	2,467	525	294	0.3%	18.2%
15%	1,546	2,486	534	313	1.4%	19.1%
Change in market-weighted average baseline engine costs						
Base (56.5%)			0	0		
50%			-94	-88		
45%			-169	-158		
40%			-245	-227		
35%			-321	-297		
30%			-396	-365		
25%			-472	-434		
20%			-504	-459		
15%			-546	-497		
Net change in compliance costs (CO_2 technology plus baseline engine savings)						
Base (56.5%)			0	0	0.0%	15.9%
50%			-30	-35	0.0%	15.9%
45%			-33	-57	0.0%	16.2%
40%			-31	-79	0.0%	16.5%
35%			-28	-101	0.0%	16.8%
30%			-20	-122	0.0%	17.1%
25%			-11	-144	0.0%	17.4%
20%			21	-165	0.3%	18.2%
15%			-12	-184	1.4%	19.1%

Costs in this table–and in all report figures unless otherwise specified–are total retail level costs, exclusive of taxes. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added to direct manufacturing costs to derive total retail level cost estimates.

(b) Electric vehicle optimization strategy

Diesel market share	Per-vehicle compliance costs		Change in compliance costs from baseline		Electric vehicle market share	
	Lower bound compliance costs	Upper bound compliance costs	Lower bound compliance costs	Upper bound compliance costs	Lower bound compliance costs	Upper bound compliance costs
Exclusive of savings related to the elimination of baseline diesel engine cost premiums						
Base (56.5%)	652	1,880	0	0	14.8%	25.9%
50%	686	1,916	34	36	15.6%	26.6%
45%	709	1,945	57	65	16.3%	26.9%
40%	731	1,976	79	96	17.2%	27.4%
35%	753	2,007	101	127	18.0%	28.0%
30%	775	2,037	123	157	18.7%	28.4%
25%	796	2,067	144	187	19.5%	29.0%
20%	797	2,075	145	195	20.2%	29.5%
15%	811	2,097	159	217	21.0%	30.2%
Change in market-weighted average baseline engine costs						
Base (56.5%)			0	0		
50%			-79	-76		
45%			-142	-137		
40%			-203	-198		
35%			-263	-257		
30%			-322	-315		
25%			-380	-373		
20%			-404	-396		
15%			-437	-429		
Net change in compliance costs (CO_2 technology plus baseline engine savings)						
Base (56.5%)			0	0	14.8%	25.9%
50%			-45	-40	15.6%	26.6%
45%			-85	-72	16.3%	26.9%
40%			-124	-102	17.2%	27.4%
35%			-162	-130	18.0%	28.0%
30%			-199	-158	18.7%	28.4%
25%			-236	-186	19.5%	29.0%
20%			-259	-201	20.2%	29.5%
15%			-278	-212	21.0%	30.2%

Costs in this table–and in all report figures unless otherwise specified–are total retail level costs, exclusive of taxes. Basic technology costs are estimated in terms of direct manufacturing costs, which are essentially the capital cost of the technology to the vehicle manufacturer. Such costs do not include various expenses such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. These so-called indirect costs are added to direct manufacturing costs to derive total retail level cost estimates.

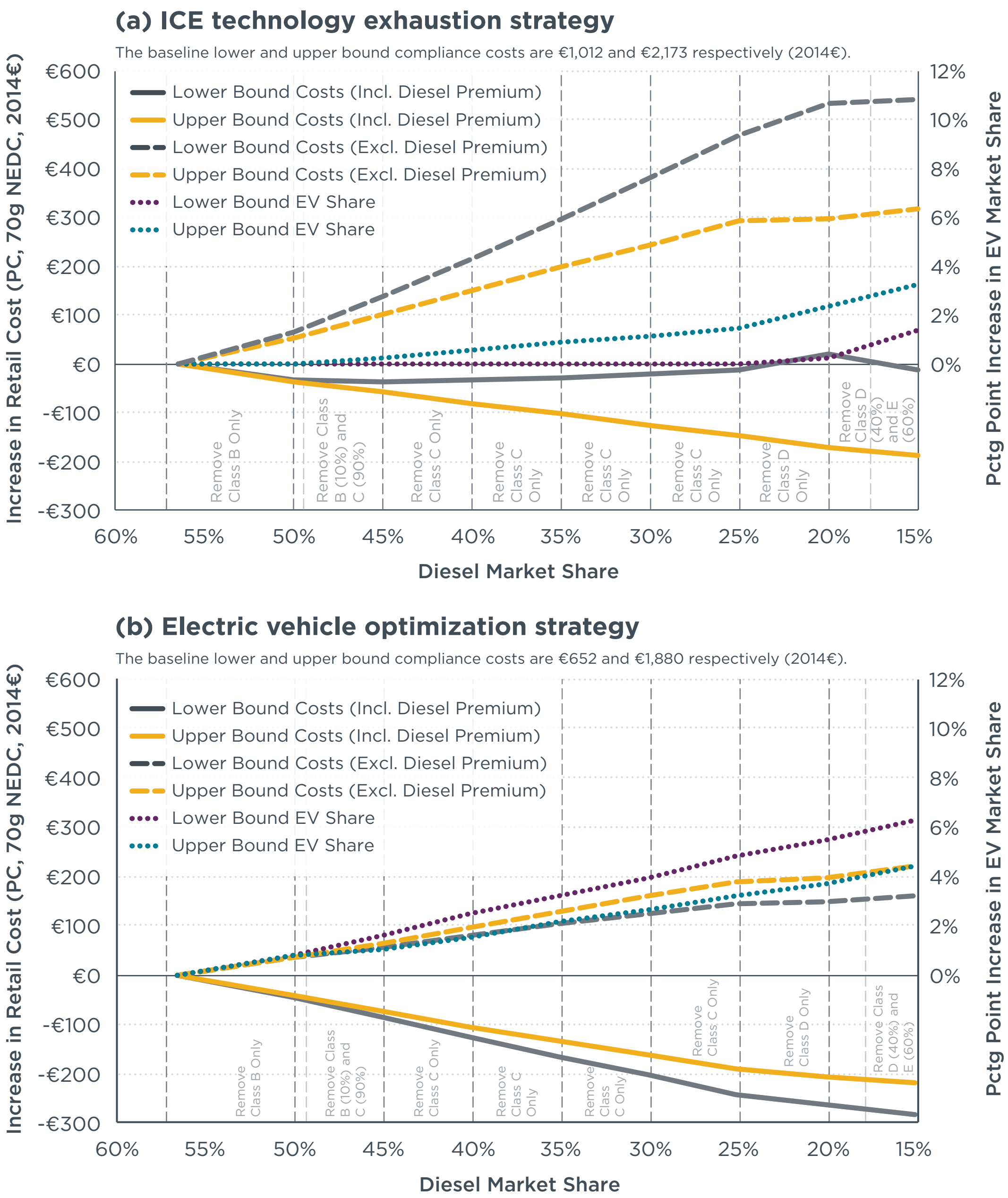

Figure 12. Change in compliance costs for (a) ExhICE strategy, and (b) EV optimization strategy.

As indicated, CO_2 technology costs increase as diesel market share decreases. Costs rise by as much as 310–530 euros[17] under an ICE technology exhaustion strategy, with associated electric vehicle market share increasing by as much as one to three percentage points. Under an electric vehicle cost optimization strategy, costs rise by as much as 160–220 euros, with associated electric vehicle market share increasing by as much as four to six percentage points. When savings associated with the elimination of baseline diesel engine premiums are considered, net costs become negative under all but a single evaluated scenario. Net savings of 10–180 euros accrue for the lowest diesel market share scenario under an ICE technology exhaustion strategy, and 210–280 euros under an electric vehicle cost optimization strategy. It is important to recognize that these costs, and savings, do not capture the value of reduced NO_x emissions expected with a shift from diesel to gasoline and electric passenger cars. These co-benefits are evaluated in the following section.

17 All values in this paragraph are in terms of 2014 euros.

4. INFLUENCE OF DIESEL MARKET SHARE ON NO_X EMISSIONS

The earlier analysis demonstrates that the costs to comply with a 70 g/km CO_2 target can be lowered with a shift from diesels to gasoline and electric vehicles. This reduction in compliance costs—which is a result of the elimination of diesel engine premiums and the relatively modest cost of additional gasoline technology—is greatest if manufacturers also pursue an electric vehicle optimization strategy to meet the CO_2 target.

In addition to reducing the cost of compliance with CO_2 standards, such a shift from diesels to gasoline and electric vehicles could benefit air quality through reduced tailpipe emission of air pollutants. High NO_X emissions from diesel cars in particular have been associated with one third of NO_2 exceedances at street-level monitoring stations in the EU (Kiesewetter & Borken-Kleefeld, 2016). Moreover, diesel cars account for more than 80% of NO_X emissions from the EU passenger car fleet, and new Euro 6 diesel cars emit approximately 9 times as much NO_X as Euro 6 gasoline cars (Miller & Franco, 2016). For these reasons, in this section we quantify the potential effect of a reduced diesel market share on NO_X emissions.

4.1 METHODS

This analysis addresses two key research questions:

(1) What is the influence of diesel market share in general on projections of NO_X emissions from EU passenger cars?

(2) What are the implications of a smaller diesel market share for NO_X emissions under scenarios that explicitly model compliance with a 70 g/km CO_2 target in 2025?

The first question has been addressed in an earlier ICCT study on the projected impacts of the RDE regulation on new car NO_X emission factors and in-use NO_X emissions in the EU (see Miller & Franco, 2016). That analysis showed that future development of the RDE regulation could reduce NO_X emissions from the EU passenger car fleet by 210,000 to 360,000 tons per year in 2030 compared to a counterfactual scenario with no further development of the RDE, depending on the future market share of diesel cars. Likewise, the marginal NO_X benefits of a reduced diesel market share depend on the stringency of the RDE regulation, ranging from 30,000 tons per year under an Accelerated RDE+ program to 180,000 tons per year in 2030 under a Baseline RDE program. The marginal NO_X benefits of a reduced diesel market share are inversely correlated with the stringency of the RDE program, because a more stringent program would result in cleaner diesels. The results of that analysis are not directly applicable to the second research question, however, because the assumptions for a smaller diesel market are somewhat different.

The RDE analysis assumed that the new diesel car market share declines to slightly less than 20% in 2030, with gasoline cars making up for 100% of the loss in diesel market share. In this analysis, we assume the diesel market share declines to 15% by 2025, with a combination of gasoline, plug-in hybrid, and battery-electric cars making up for the loss in diesel market share. Figure 13 summarizes the assumptions for market share applied in this analysis. The reference projections are consistent with the previous RDE analysis (Miller & Franco, 2016) and reflect a relatively stable diesel market share. The two new sets of projections reflect the lower bound and upper bound market shares estimated under two manufacturer compliance strategies for a 70 g/km CO_2 target (see Section 3.3). As shown in Figure 13, the lower bound and upper bound estimates for electric vehicle market share under the ICE technology exhaustion strategy are similar to the reference projections (lower bound) and the lower bound of the EV optimization strategy (upper bound). Whereas assessing NO_x emissions under the market shares of the ICE technology exhaustion strategy would be largely duplicative—the upper bound of the ICE technology exhaustion strategy would have nearly identical emissions to the lower bound of the EV optimization strategy, and the lower bound of the ICE technology exhaustion strategy would fall somewhere in between the emissions of the reference projections and lower bound of the EV optimization strategy—the following analysis of NO_x emissions applies only to the reference projections and the lower bound and upper bound of the EV optimization strategy.

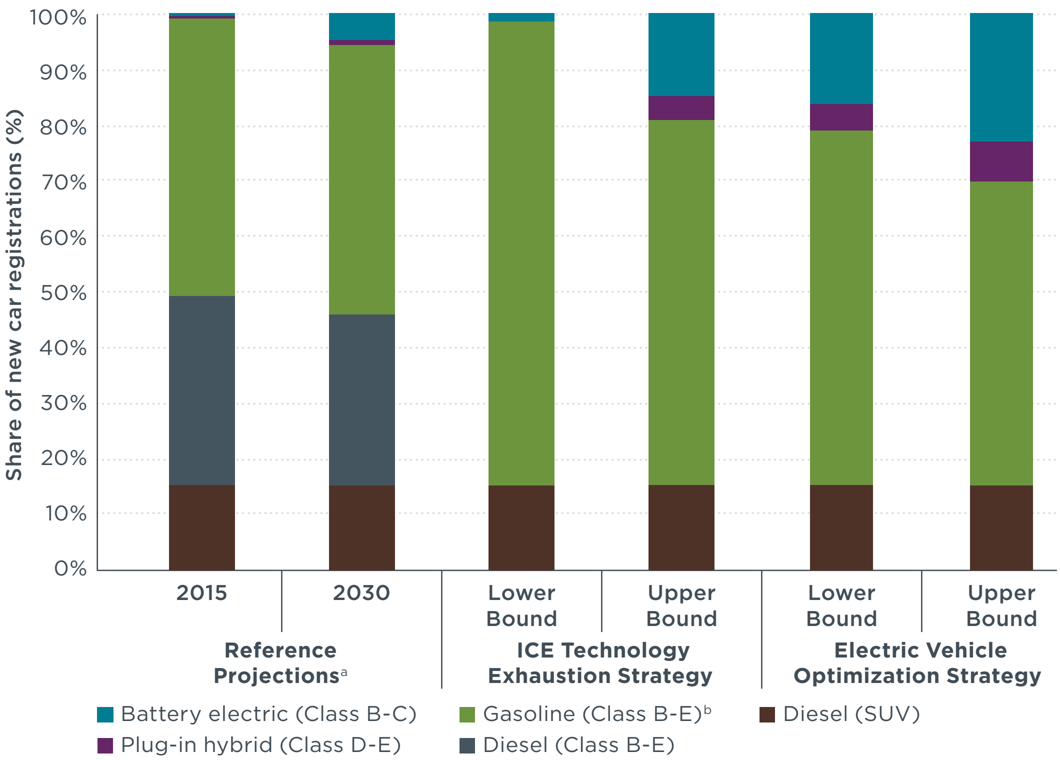

Figure 13. Share of new car registrations in the EU by fuel type, 2015 and 2030.

[a] Reference projections for new car market shares are unchanged from SIBYL version 4.0 – July 2015 (EMISIA SA, 2016). The projected market share for diesel cars in 2015 and 2030 is slightly lower than indicated by the FEV data (2014 era) used for ICCT's cost curve analysis. This difference of projections versus actual has no material effect on the NO_x emission projections for 2030, however, because these are determined by the assumptions about future market shares developed in this analysis.

[b] Gasoline (Class B–E) also includes a small share of vehicles powered by biofuels (flex-fuel), compressed natural gas, and liquefied petroleum gas.

As in the previous analysis (Miller & Franco, 2016), EU passenger car fleet NO_x emission projections are developed using a version of Emisia SA's Sibyl model, modified to accommodate ICCT's estimates of new car NO_x emission factors and future market shares by fuel and technology. Given the substantial influence of the future RDE regulation on passenger car NO_x emissions, each NO_x emission scenario reflects a unique combination of assumptions for the development of RDE and future market shares by fuel type.

Key elements of these six NO_x emission scenarios are given in Table 4. Scenarios 1–3 assume that a baseline RDE program reduces real-world NO_x emissions of new Euro 6 diesel cars from 5.7 times the Euro 6 limit of 80 mg/km to about 4 times that limit, reflecting a worst-case scenario without further developments beyond the adopted first and second RDE packages (see Miller & Franco, 2016). Scenarios 4–6 consider an improved program that reduces real-world NO_x emissions of new Euro 6 diesel cars to 1.2

times the Euro 6 limit of 80 mg/km using Accelerated RDE+. These emission reductions are achieved via the introduction of expected changes to the RDE program—the third and fourth RDE packages—as well as further improvements previously recommended by the ICCT. The Accelerated RDE+ program assumes the implementation of cold-start provisions in 2018, market surveillance and tightened conformity factors in 2020, and further improvements in 2022. These include real-world emissions monitoring via remote sensing, expanded boundaries of the RDE test procedure, and publication of RDE test results to enable independent verification.[18]

Scenarios 1 and 4 apply the reference projections for market shares shown in Figure 13. These scenarios are identical to the similarly-named scenarios in the 2016 Miller and Franco analysis. Scenarios 2 and 5 apply the lower bound EV market shares for the EV optimization strategy, whereas scenarios 3 and 6 apply the upper bound market shares for that strategy. EVs are assumed to be predominantly BEVs for segments C and smaller and PHEVs for segments D and larger. The projected increase in the market share of BEVs and PHEVs under the EV optimization strategy translates to an annualized 45%–50% increase in BEV sales from 2015–2025 and a 34%–39% annualized increase in PHEV sales. These rates of EV sales growth are reasonable considering the 65% annualized increase in global EV sales observed between 2012 and 2015 (Mock, 2016).

Table 4. Definition of NO_x emission scenarios

#	Scenario	Diesel car NO_x emission factor at end RDE step	Share of new car registrations in 2030	
			Diesel	PHEV + BEV
1	**Baseline RDE, reference projections**	320 mg/km (4x Euro 6 limit)	46%	5%
2	**Baseline RDE, EV optimization strategy, lower bound**		15%	21%
3	**Baseline RDE, EV optimization strategy, upper bound**		15%	30%
4	**Accelerated RDE+, reference projections**	96 mg/km (1.2x Euro 6 limit)	46%	5%
5	**Accelerated RDE+, EV optimization strategy, lower bound**		15%	21%
6	**Accelerated RDE+, EV optimization strategy, upper bound**		15%	30%

4.2 RESULTS

Figure 14 shows the impacts of these scenarios on projected NO_x emissions from the EU passenger car fleet from 2015–2030; several key insights follow. First, over this period, NO_x emissions would decline by 46% under the least ambitious scenario and by 70% under the most ambitious scenario—a difference of 420,000 tons of NO_x per year. Second, the variation in the market shares of gasoline cars, BEVs, and PHEVs under an EV optimization strategy—reflected in the difference between the lower bound and upper bound assumptions—has very little impact on total fleetwide NO_x emissions. The insensitivity of fleetwide NO_x emissions to gasoline versus electric vehicle market shares reflects the very high NO_x emissions of diesel cars compared to either alternative—recalling that pre-RDE Euro 6 diesel cars emit approximately 9 times as much NO_x per kilometer as Euro 6 gasoline cars.

18 According to the latest regulatory developments that include approval of the third package and technical work on the fourth package, the evolution of the RDE standard will go beyond the baseline scenarios and likely more closely follow the accelerated pathway. Some of the elements of the RDE program will be covered in separate pieces of legislation, notably the proposed new regulation for a new EU type-approval framework.

Third, the influence of a reduced diesel market share depends largely on the future development of the RDE regulation, in that a less stringent RDE increases the benefits of a smaller diesel market share. In 2030, the NO_x benefits of a smaller diesel market share range from approximately 60,000 tons per year (with Accelerated RDE+) to approximately 260,000 tons per year (with baseline RDE). In other words, the NO_x benefits of reducing the diesel market share—consistent with meeting a 70 g/km CO_2 target at reduced cost—equal a reduction of 10-28% compared to a baseline scenario and are equivalent to the sum of all NOx emissions in a country of the size of the Netherlands.

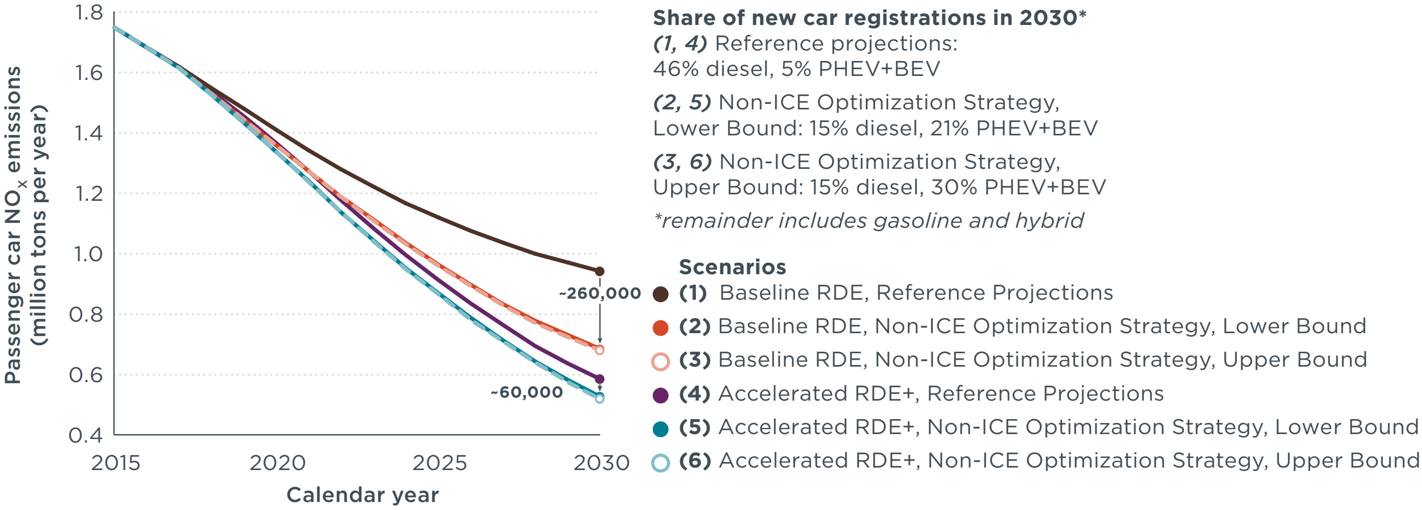

Figure 14. EU passenger car fleet NO_x emissions by scenario, 2015–2030.

5. CONCLUSIONS

This paper examined the influence of potential changes in diesel market share on costs of compliance with CO_2 standards and passenger car NO_x emissions in Europe. Since the 1990s, most European governments have promoted diesel-powered cars, in many cases based on their expected CO_2 emission savings. In reality, substantial fleetwide CO_2 emission reductions from 2001 to 2015 have been achieved in the Netherlands, Germany, and France without major increases in diesel market share. Similar effects are seen for the United States and Japan. On average, over all vehicle segments, current CO_2 emissions from diesel and gasoline cars in the EU are roughly at the same level. A comparison across fueling types within the lower medium segment, which allows for a like-for-like comparison, shows that conventional diesel cars in 2015 emitted around 17% less CO_2 than conventional gasoline cars, whereas hybrid electric vehicles (excluding plug-in hybrids) emitted 32% less.

A comparison of average retail prices within the lower medium segment in Germany shows that hybrid cars became cheaper than diesel cars from 2013 to 2015. Combined with the lower CO_2 emissions of hybrids, the price premium of cutting CO_2 emissions, on average, therefore is significantly higher for diesel cars than for hybrids. This means that the same or greater CO_2 reductions can be achieved more cheaply through purchasing hybrid cars instead of diesel cars.

Previously, ICCT developed CO_2 cost curves to describe the cost of compliance with various fleet average CO_2 targets in the EU, assuming the diesel market share would remain constant over time. This study re-evaluated these cost curves to estimate the differential compliance costs of changing diesel passenger car market shares. The analysis revealed that a reduced diesel market share would have little effect on CO_2 standard compliance costs. In fact, a lower diesel market share can actually result in net cost savings, because modest cost increases from additional gasoline technology and slightly more electric vehicles are outweighed by moving from more expensive conventional diesel engines to cheaper conventional gasoline engines. The net costs of meeting a 70 g/km NEDC standard would be reduced by about 10–280 euros, in terms of 2014 euros, in response to a decline in the market share of diesel cars from 56.5% to 15%. Ignoring savings that accrue with the elimination of diesel engine cost premiums, compliance costs for a 70 g/km passenger car NEDC standard increase by only 160–530 euros, again at the 2014 euro level, as diesel car market shares decline from 56.5% to 15%. Thus, the net cost of CO_2 reduction in the EU is relatively insensitive to diesel market share, but net costs tend to decline with decreasing diesel market share.

Because conventional diesel passenger cars emit more NO_x compared to conventional gasoline and gasoline hybrid cars, reducing the diesel market share could also benefit air quality through reduced tailpipe NO_x emissions. An analysis of six NO_x emission scenarios shows that a reduced diesel market share could reduce NO_x emissions by 10%–11% under an Accelerated RDE+ program, or 27%–28% under a worst-case scenario without improvements to the RDE program. In 2030, the fleetwide NO_x emission reductions from a diminished diesel market share range from 60,000 to 260,000 tons per year, with smaller NO_x reductions from diesel market share under a more stringent RDE program. These NO_x emission reductions from a smaller EU diesel market share are consistent with meeting a 70 g/km CO_2 target at reduced cost.

Future analysis could evaluate the influence of reduced emissions on concentrations of NO_2, $PM_{2.5}$, and ozone using global or regional air quality modeling. $PM_{2.5}$- and ozone-related health impacts can also be assessed by combining modeled concentration changes with epidemiologically derived health impact functions.

In summary, these findings show that a reduced market share of diesels in the passenger car market would not substantially affect the cost of compliance with stringent CO_2 standards and would have benefits from reduced fleetwide NO_x emissions. Considering the higher cost of conventional diesel engines compared to conventional gasoline engines, transitioning to more advanced gasoline technology and electrified vehicles—including hybrid, plug-in hybrid, and battery electric vehicles—would actually reduce the cost of complying with a hypothetical 70g/km CO_2 standard for 2025. As technology progresses and batteries become cheaper, these net cost savings could grow. Meanwhile, a smaller diesel market share would reduce fleetwide NO_x emissions. These NO_x reductions, however, are small compared to the reductions that would come from strengthening the RDE program.

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