IMPACT OF IMPROVED REGULATION OF REAL-WORLD NO$_X$ EMISSIONS FROM DIESEL PASSENGER CARS IN THE EU, 2015–2030

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EXECUTIVE SUMMARY

The transport sector is the largest contributor of nitrogen oxide (NO_x) emissions in the European Union (46% in 2013), with 80% of the emissions coming from diesel-powered cars, vans, heavy trucks, and buses (European Environment Agency, 2015). Excess NO_x emissions from diesel cars have remained high, largely due to a growing gap between emission certification limits of Euro 4 and Euro 5 standards (measured in laboratory testing) and "real-world" emissions of diesel cars operating on the roads. Recent investigations by German, Dutch, French, and British national authorities point to a failure of both Euro 5 and Euro 6 standards, specifically the compliance and enforcement mechanisms defined in the regulations, to ensure that manufacturers properly calibrate engine and aftertreatment devices to achieve low real-world NO_x emissions from diesel cars.

Beginning in 2017, the EU's emissions type-approval procedure for passenger cars will include a new real-driving emissions (RDE) test conducted using on-board portable emissions measurement systems (PEMS). The RDE test is intended to supplement the laboratory certification tests, which are currently the only demonstration of compliance with vehicle emissions standards required of manufacturers. Under the new type-approval system, to obtain a certificate of conformity with Euro 6 standards, manufacturers must demonstrate that new vehicle models pass the RDE test, which measures NO_x emissions in on-road operation rather than in the precisely controlled drive cycle and environmental conditions of a test laboratory.

The RDE test protocol is being defined over four increasingly stringent "regulatory packages" (regulations), the first two of which have already been adopted. The first RDE package took effect on January 1, 2016, and requires new diesel car types to be tested using PEMS for monitoring purposes. The second package introduced a so-called conformity factor (CF), or not-to-exceed multiplier, for RDE test results compared to Euro 6 NO_x emission limits (80 mg/km for diesel cars). Under the second package, the conformity factor for all new car models will be tightened from 2.1 by September 2017 to 1.5 by January 2020.

Two additional packages have been proposed by the Real-Driving Emissions–Light-Duty Vehicles (RDE-LDV) working group at the European Commission. Under the third package, the RDE test procedure would be extended to cover cold-start emissions, measure particulate number in addition to NO_x, and include a provision for how the test deals with aftertreatment system regeneration events during the RDE test. The fourth package, scheduled for discussion and adoption in 2017, is expected to extend the RDE test to cover in-use vehicles rather than only prototypes and include a provision that allows independent testing by third parties to trigger action by regulatory authorities if deviations from type-approval measurements are found. Such independent testing would provide important safeguards to verify the compliance of vehicles in various conditions of the RDE procedure.

The extent to which EU regulators will succeed in reducing real-world NO_x from passenger cars is critically linked to the future development of the RDE and type-approval framework to improve compliance and enforcement and eliminate the widespread circumvention by diesel vehicle manufacturers of defeat device prohibitions in the vehicle emissions regulations. As currently formulated, the RDE and type-approval framework do not go far enough to eliminate the incidence of defeat devices and poor aftertreatment system calibrations and ensure that manufacturers achieve low NO_x in all real-world driving conditions.

The International Council on Clean Transportation (ICCT) has previously outlined five specific recommendations to strengthen the RDE regulation by building on the current framework (Franco & Mock, 2015). Some of these modifications are in line with the European Commission's proposal for an overhauled light-duty type-approval framework[1] and the expected content of the third and fourth RDE packages, but others go beyond them (e.g., public access to type-approval information and expanded test boundaries). This white paper examines the potential impact of the RDE regulation and ICCT's proposed modifications on real-world emission factors of new diesel cars and projected passenger car fleet NO$_X$ emissions in the EU through 2030.

The analysis develops a Baseline RDE scenario, which reflects the RDE program as currently formulated (first and second packages), and two different RDE+ pathways with increasing levels of ambition. These pathways introduce successive improvements—termed RDE+a, RDE+b and RDE+c—based on ICCT's proposed modifications. The Conservative RDE+ pathway assumes the implementation of cold-start provisions (RDE+a) in 2020 followed by market surveillance and tightened conformity factors in 2023 (RDE+b). The Accelerated RDE+ pathway assumes the implementation of improvements in all five key areas on an accelerated implementation calendar, with the phase-ins of the different steps taking place in 2018, 2020, and 2022. The third step of the Accelerated RDE+ scenario, RDE+c, goes beyond the provisions that are expected under the third and fourth RDE packages. These additional measures include real-world emissions monitoring via remote sensing, expanding the boundaries of the RDE test procedure, and publishing RDE test results to enable independent verification.

The results of emission-factor modeling indicate that the Baseline RDE scenario will reduce real-world NO$_X$ emissions of new Euro 6 diesel cars from 5.7 times the Euro 6 limit of 80 mg/km to approximately 4 times that limit (Figure ES-1). The Conservative RDE+ scenario is estimated to further reduce this emission factor to 2.1 times the Euro 6 limit. In contrast, the Accelerated RDE+ scenario is estimated to achieve a real-world NO$_X$ emission factor of 1.2 times the Euro 6 limit by 2022. Only the most stringent step of the Accelerated RDE+ program, RDE+c, is estimated to effectively eliminate the presence of defeat devices and poor NO$_X$ emissions control implementations among new diesel cars.

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1   See http://www.theicct.org/proposed-new-type-approval-framework-eu-policy-update
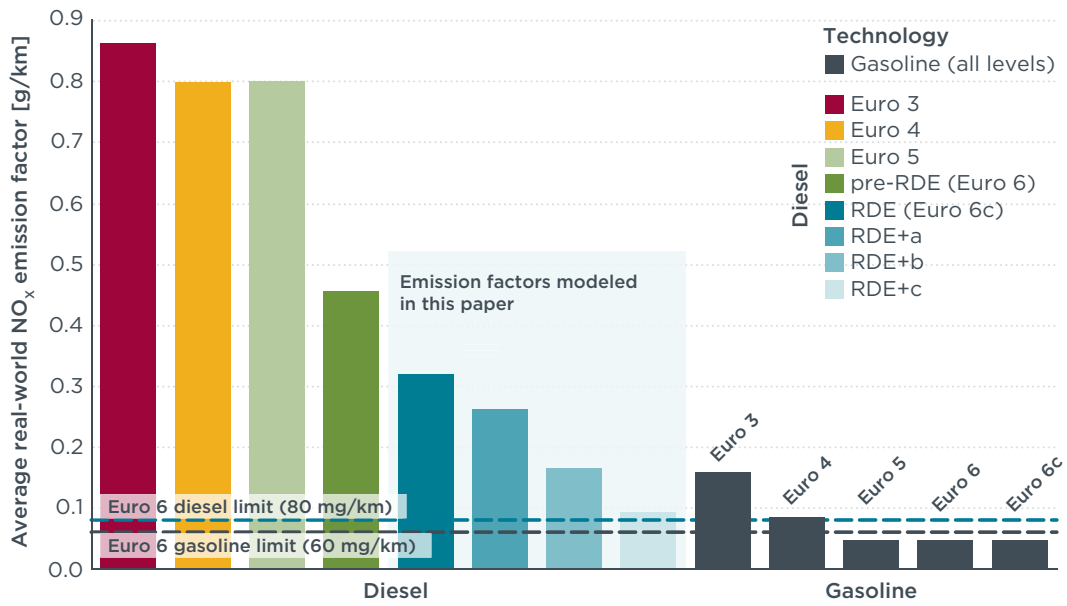
Figure ES-1. Average real-world NO$_x$ emission factors for passenger cars in the EU-28, 2015.

Figure ES-2 shows the implications of these real-world NO$_x$ emission factors for projected passenger car emissions in the EU-28 through 2030. Although NO$_x$ emissions decrease under all scenarios, hundreds of thousands of tons (NO$_x$) could be avoided per year with each additional set of RDE testing improvements. Most noteworthy, if the market share of new diesel cars were to decrease to less than 20% by 2030, the Accelerated RDE+ scenario would still achieve an annual reduction of 210,000 metric tons of NO$_x$ in 2030 compared to the Baseline RDE.
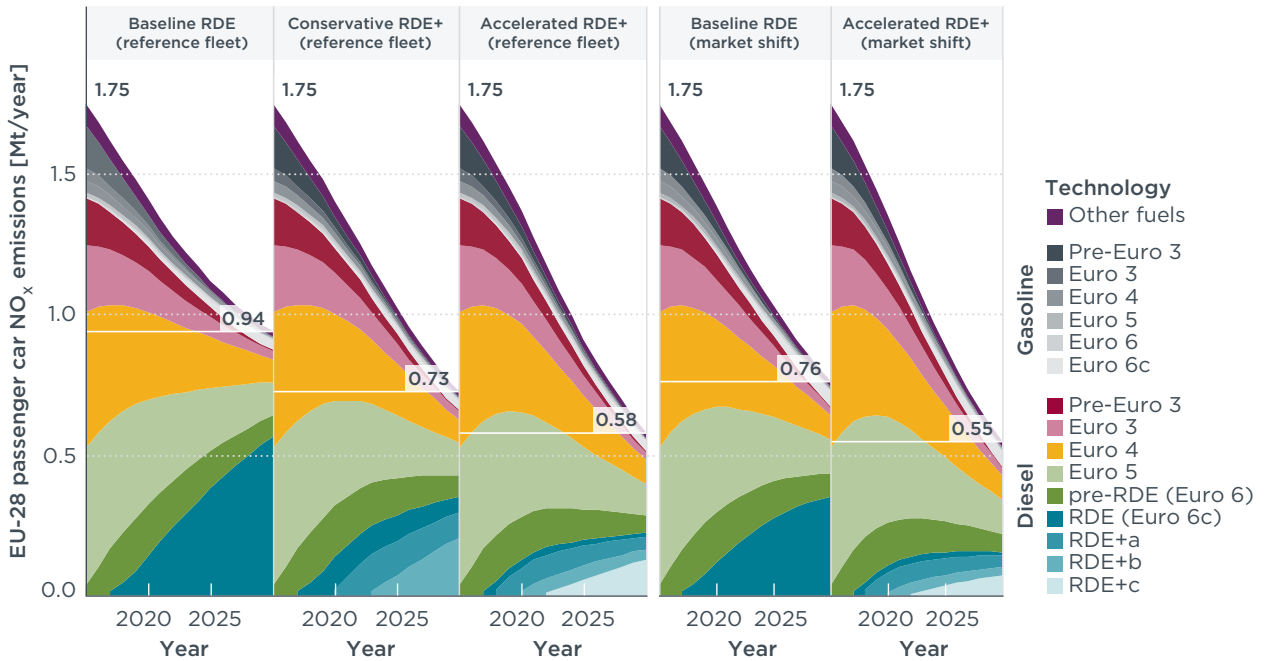

Figure ES-2. Projections of real-world NO$_x$ emissions for passenger cars in the EU-28, 2015 through 2030.

Figure ES-3 illustrates the impacts of a low-emission zone (LEZ) on fleet average passenger car NO$_x$ emissions in a hypothetical city with the EU-average fleet technology mix. Without an LEZ, the average in-use passenger car is projected to emit several times

the Euro 6 diesel NO$_X$ limit in 2030,[2] in large part due to the continued presence of Euro 4 and Euro 5 diesel passenger cars. An LEZ would have substantial NO$_X$ benefits immediately upon implementation (2020–2026). The immediate emission reductions are achieved by limiting the activity of Euro 4 and Euro 5 diesel passenger cars, while sustained emission reductions are enabled by the improved RDE program. Whereas the Baseline RDE could reduce average car NO$_X$ emission factors by close to 50% by 2030 (compared to 2015 emission levels), an LEZ implemented in conjunction with the Accelerated RDE+ could achieve this level of NO$_X$ reduction by 2022 and achieve an 80% reduction by 2030.
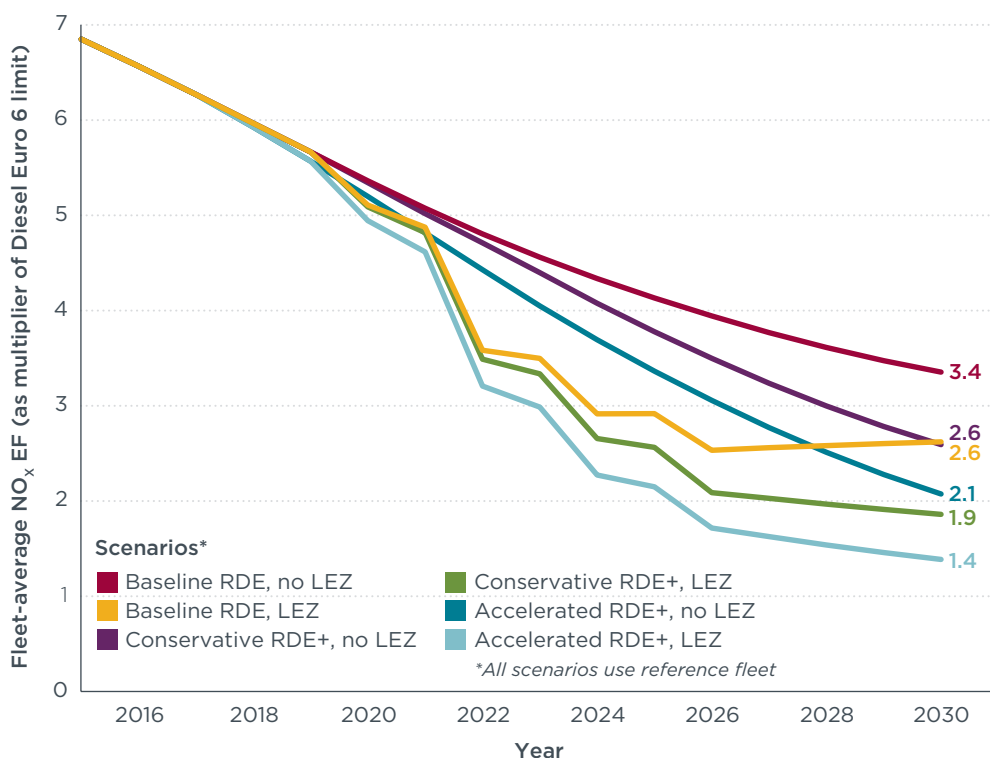
Figure ES-3. Impact of LEZ on average passenger car NO$_X$ emissions, 2015–2030.

The prospect that real-world NO$_X$ emissions from diesel cars will remain higher than emission limits highlights the importance of further developing the RDE program to incorporate the improvements evaluated in this paper as well as considering a Euro 7 standard that tightens NO$_X$ emission limits for both diesel and gasoline cars. The NO$_X$ emissions projections here highlight the importance of strengthening the RDE and associated compliance and enforcement practices, regardless of the expected future market share of diesel cars. In addition to these actions to reduce NO$_X$ emissions at the EU-level, we find that well-designed LEZs can be an effective local-level action to quickly reduce in-use NO$_X$ emissions from passenger cars and accelerate the benefits of a strengthened RDE program.

2   To convert to an absolute emission factor, multiply by 80 mg/km.

1. BACKGROUND

In this paper, we have modeled reductions in the real-world nitrogen oxide (NO_x) emissions of future European diesel passenger cars. These reductions are driven by increasingly stringent emission standards that rely heavily on on-road tests at the type-approval stage and by improved enforcement practices. The combination of these two elements is required to tackle the problem of real-world NO_x emissions from diesel cars, which remains one of the main unresolved issues in the Euro emission standards. In this section, we provide some background information to help the reader understand the technical and policy issues that have contributed to the current situation.

1.1 REAL-WORLD EMISSIONS OF EURO 3 TO EURO 5 DIESEL CARS

Historically, diesel passenger cars have had higher in-use emissions of NO_x and particulate matter (PM) than their gasoline counterparts. The Euro 5b standard, which applied to all diesel sales and registrations beginning in January 2013, was successful in requiring mass adoption of diesel particulate filters (DPFs) and therefore in lowering real-world PM emissions. However, the Euro 5 NO_x emission limit of 180 mg/km was only reduced by 28% from the Euro 4 limit, allowing manufacturers to pass the certification test without using dedicated NO_x aftertreatment control technologies (e.g., lean NO_x traps [LNT] or selective catalytic reduction [SCR]). Moreover, this limit applied an outdated measurement protocol (New European Driving Cycle [NEDC]) and was not supported by on-road compliance and enforcement requirements for in-use vehicles. As a result, the real-world NO_x emission factor for Euro 4 and Euro 5 passenger cars (as estimated from long-term remote sensing studies and other emission modeling exercises) is approximately 800 mg/km, roughly 3.2 times the Euro 4 limit of 250 mg/km and 4.4 times the Euro 5 limit of 180 mg/km (Figure 1).

1.0

0.5

Euro 3
(2000)

0.8

0.25

Euro 4
(2005)

0.8

0.18

Euro 5
(2009)

0.6

0.08

Euro 6 (pre-RDE)
(2014)

-- Euro emission limit [g/km]   ■ On-road measured values (Carslaw et al., 2011; Franco et al., 2014)
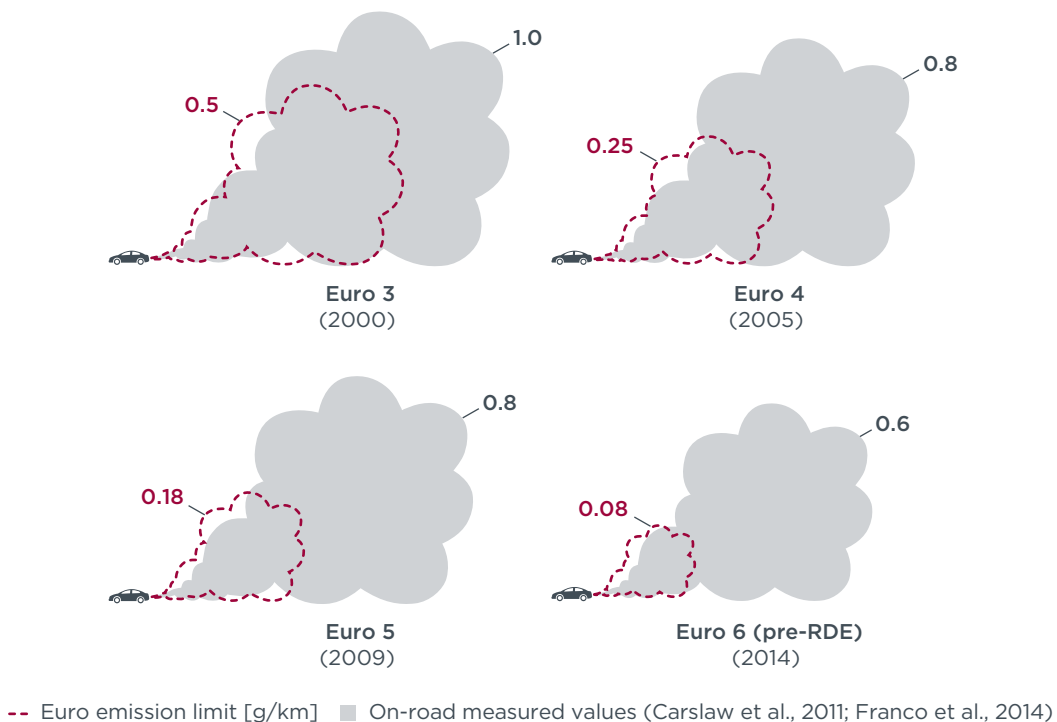
Figure 1. Illustration of the evolution of real-world NO_x emissions from European diesel passenger cars in relation to the regulated emission limits, 2000–2014 (ICCT, 2016).

1.2 EURO 6 AND THE DIESEL EMISSIONS SCANDAL

Since September 2015, all new diesel passenger cars registered in the EU must meet the Euro 6 standard, which lowered the NO$_X$ emission limit to 80 mg/km;[3] however, there is plenty of experimental evidence pointing to a disappointing on-road NO$_X$ emission performance of current Euro 6 diesel cars: several studies conducted with on-board portable emissions measurement systems (PEMS) on a limited number of vehicles (Franco et al., 2014; Kadijk et al., 2015; Ligterink et al., 2013) have estimated a real-world NO$_X$ emission factor of 450–600 mg/km (5 to 7 times the regulated limit) for early Euro 6 vehicles tested during the voluntary phase-in period of the standard (2012–2014). Investigations recently carried out or sponsored by German, Dutch, French, and British national authorities following the diesel emissions scandal (BMVI, 2016; Heijne et al., 2016; MEEM, 2016; UK Department for Transport, 2016) support these initial findings and point to a generalized failure of the Euro 5 and Euro 6 standards and their compliance and enforcement mechanisms to ensure that manufacturers properly calibrate engine and aftertreatment devices to achieve low real-world NO$_X$ emissions from diesel cars (Franco, 2016).

A recurring finding of Euro 6 emission investigations is that there is a large scatter in the real-world NO$_X$ results, with a minority of the vehicles emitting up to 10–15 times the regulated limit (see an example from the British national investigation in Figure 2). Measurements conducted on a chassis dynamometer (Yang et al., 2015b) on 73 Euro 6 diesel cars show a similar scatter in the results and indicate that, whereas the Euro 6 standard effectively forced most diesel car manufacturers to equip their Euro 6 offerings with dedicated NO$_X$ control systems (Yang et al., 2015a), these technologies are not being applied to their full extent during real-world operation. This is made possible by the "active" nature of the emission control systems (i.e., they are intelligently managed by the vehicle's electronic control unit based on a wide variety of input parameters) and likely motivated by convenience, cost, durability, and fuel consumption penalties deriving from the application of optimized low-NO$_X$ control strategies (Ntziachristos et al., 2016a).[4]

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3   This represents a 56% reduction from the Euro 5 limit, but still a higher limit value than what is allowed for gasoline passenger cars (60 mg/km).

4   For example, LNT technology carries a fuel consumption penalty of approximately 3–4% (Yang et al., 2015a). The hardware required by SCR technology is typically more expensive than LNT and carries an additional inconvenience (and cost) penalty in the form of periodical diesel exhaust fluid (AdBlue) top-ups.

EURO 5 DIESEL CARS

EURO 6 DIESEL CARS
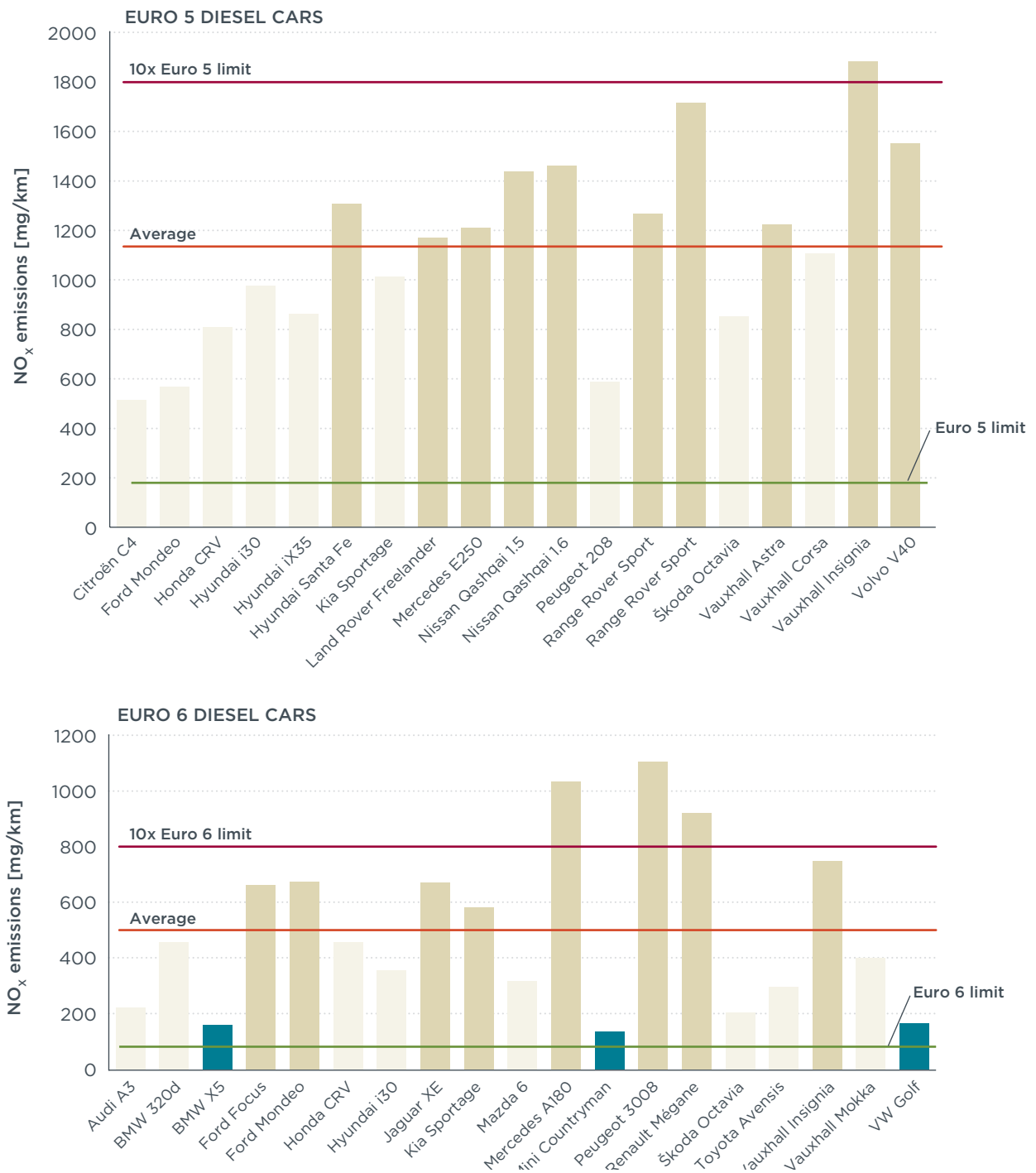
Figure 2. NO_x emissions from Euro 5 and Euro 6 passenger cars measured by UK authorities during real-driving, on-road tests (driving conditions differ across tests; Franco, 2016). Data source: UK Department for Transport (2016).

1.3 THE EUROPEAN REAL-DRIVING EMISSIONS REGULATION

As a policy response to the underperformance of the Euro 5 standard for diesel NO_x, the European Commission started a technical stakeholder group to design a complementary, real-world emissions test to be performed as an additional step for the type approval of emissions from light-duty vehicles in Europe. The project started before the Volkswagen defeat device scandal, although the scandal did attract a great deal of public attention to the regulation, as well as political pressure. Beginning in January 2017, the European

Union's (EU's) emissions type-approval procedure for passenger cars will include a new real-driving emissions (RDE) test conducted using PEMS. The RDE test is, in principle, less vulnerable to defeat devices and "narrow" emission aftertreatment calibrations, because it is a realistic on-road test with several uncontrolled random elements (e.g., traffic or weather conditions).

2. METHODOLOGY

Our research methodology is divided into three steps (see overview in Figure 3).

For the first step (Section 2.1), we propose two realistic policy pathways for further development of the European RDE regulation. The pathways are designed to reflect planned and expected technical improvements to the currently adopted RDE regulation, as well as adoption of a strengthened RDE regulation (RDE+).

As a second step (Section 2.2), we modeled the evolution of real-world NO_x emission factors that would result from the implementation of the strengthened RDE+ regulation. An uncertainty analysis using a Monte Carlo simulation is included.

As a third and final step (Section 2.3), the modeled real-world emission factors were combined with EU passenger car stock and activity data and projections up to the year 2030 to forecast the trends in fleet-wide passenger car NO_x emissions under several scenarios that cover different levels of ambition for the RDE+ regulation and different evolutions of the diesel market share in the EU. The effect of implementation of a low-emission zone (LEZ) in a hypothetical city with the EU-average passenger car fleet technology mix is also investigated.

The time frame for the assessment is 2015–2030, approximately corresponding to the point where the European car fleet will be dominated by passenger cars certified to Euro 6. The proposed implementation calendar takes into account the level of effort needed to drive the required changes.

INPUTS	METHODOLOGY STEPS	OUTPUTS
• Expected and proposed technical modifications to RDE legislation	1) Development of realistic policy pathways: • Conservative RDE+ • Accelerated RDE+	• Definition of RDE+ steps • RDE+ implementation calendars
• ICCT Euro 6 diesel PEMS database • Expert assumptions on emissions behavior of diesel passenger cars	2) Real-world NO_x emission factor modeling (Euro 6 diesel passenger cars) and uncertainty analysis	• Detailed EFs for all RDE+ steps • EF uncertainty estimates
• Car stock and activity projections (Sibyl) • Diesel market share forecasts • RDE+ implementation calendars • Detailed EFs for all RDE+ steps	3) Scenario definition and fleet-average real-world NO_x emission projections	• Fleet-average NO_x EF projections • Real-world NO_x emission projections

Figure 3. Methodology overview.

2.1 TECHNICAL IMPROVEMENTS TO THE RDE REGULATION

The independent testing results discussed in the Background section show that a small number of Euro 6 diesel passenger cars are already achieving low on-road emission levels using current NO_x control technologies (see the vehicles indicated with blue bars in Figure 2). The objective of the RDE regulation is to close the gap between real-world NO_x emissions and regulated emission limits, effectively ensuring that all—not only a few—diesel cars achieve low real-world NO_x emission levels. In a previous analysis of the RDE regulation, the ICCT found that although the current RDE is an important step toward reducing real-world NO_x emissions, the effectiveness of the regulation could be significantly enhanced through additional technical work in five key areas (Franco & Mock, 2015). The proposed key areas for improvement concern not just the conformity factors (CFs), but also the test boundary conditions, how test vehicles are obtained, how the on-road tests are conducted, and how the test results are disseminated.

Key Area 1: Acceleration of the technical work to include cold-start emissions in the RDE test results evaluation method, with the intention to set specific, legally binding limits by 2019. Controlling cold-start emissions is especially relevant for air quality in urban environments, where short trips and low average speeds are especially common, and where high population densities amplify the health impacts. Cold-start provisions are under discussion as part of the third RDE package, slated to be completed by the end of 2016.

Key Area 2: Tightening of the conformity factors to reflect the state of the art in NO$_X$ control technologies (and the initial technical consensus proposal made by the European Commission to Member States): instead of the current values of 2.1 (for the first phase of application of RDE) and 1.5 (the "final" conformity factor from 2020), tightened NO$_X$ conformity factors of 1.5 and 1.2 could be applied to increase the stringency of the regulation and drive additional emission reductions.

Key Area 3: Expansion of the focus of the RDE regulation from type approval only (i.e., only testing pre-production, specially prepared vehicles—the so-called "golden cars") to in-use testing for compliance and enforcement purposes. Test vehicles should be obtained at random from private individuals by enforcement agencies, and tests should be conducted throughout the useful life of vehicles to monitor the durability of emission control systems. In-service conformity testing (Key Area 3)—and, to a lesser extent, the improvement of public access to information (Key Area 5)—is expected to be the focus of the fourth RDE regulatory package in 2017.

Key Area 4: Monitoring and expansion of the boundaries of the RDE test procedure. Previous experience shows that driving situations that are not covered by regulations can lead to uncontrolled—yet technically legal—emission behaviors. This is especially true for NO$_X$ emissions, which grow exponentially at higher engine loads that are currently outside the operating conditions covered by the RDE test. Independent tests to monitor the performance of vehicles outside of the boundary conditions of the on-road RDE test (e.g., ambient temperature, altitude, high speeds, and dynamic driving indicators) should be used to expand the regulated boundary conditions. This step is necessary to maintain low in-use emissions in a comprehensive set realistic of operating conditions.

Key Area 5: Improvement of public access to information and establishment of incentive plans to foster clean diesel technologies. In addition to including the result of the RDE test in the certificate of conformity and other relevant documents, vehicles that meet the Euro 6 limits during the on-road test could, for example, be granted a "certified clean" label. This would incentivize manufacturers and consumers to produce and buy clean diesel cars (see Ntziachristos et al. [2016b]), and the labels would help local authorities build their own incentive programs–most notably LEZs. The results of the on-road tests should be made easily accessible to the public, so that consumers can make informed buying decisions and manufacturers can track their progress and benchmark their vehicles against the competition. Furthermore, the widespread adoption of alternative emission measurement techniques, such as remote sensing and inexpensive on-board NO$_X$ sensors to screen the in-service fleet for high emitters, could also lower the prevalence of defeat strategies.

Taking into account the relative difficulty and expected impact of improving various areas of the RDE program, we have constructed three successive steps that could be taken to strengthen the RDE program (Table 1). Each one of these steps—termed RDE+a, RDE+b, and RDE+c—involves improvements to one or more of the key areas described previously. The derivation of emission factors for these steps is discussed in Section 2.2.

Table 1. Overview of the modeled steps for the implementation of RDE and subsequent modifications (RDE+ steps a, b, and c).

Step	Improvements	Considerations for implementation
RDE	**Adoption of baseline RDE standard** (European Commission, 2016a, 2016b) The emissions behavior of the vehicles improves under the driving conditions covered by the RDE test (mostly due to improved aftertreatment calibrations). The prevalence of defeat devices and poor real-world calibrations is estimated to remain high in this early stage.	RDE standard adopted as foreseen by the regulation (up to the so-called second regulatory package). As of 2016, the RDE standard is in the "monitoring phase," where the test is carried out at type approval but no associated emission limits are enforced.
RDE+a	**Improvement in Key Area 1 (inclusion of cold starts)** The emissions behavior of the vehicles improves during cold-start conditions (mostly due to improved aftertreatment calibrations and also to hardware changes; e.g., thermally insulated catalysts). The prevalence of defeat devices is lowered, but only to a limited degree because the focus of RDE is not on defeat device detection.	Cold-start provisions are relatively easy to address from a technology and policy perspective. The European Commission has already signaled that the inclusion of cold-start emissions in the evaluation of RDE tests will be one of the main focuses of the third RDE regulatory package (to be released in early 2017).
RDE+b	**Improvement in Key Areas 2 and 3 (tightened CF and expansion to in-service vehicles)** The emissions behavior of the vehicles is further improved under the driving conditions covered by the RDE test as a result of improved technology implementations (e.g., substitution of LNT technology for SCR). The reductions are in line with the revised CFs (Key Area 2). The prevalence of defeat devices and poor real-world calibrations is significantly reduced as a result of improved enforcement via in-service conformity tests, recall programs, and an appropriate penalty regime to deal with noncompliance (Key Area 3).	Tightening the conformity factors should be feasible as on-road emissions data of vehicles with good implementations of NO_x control technologies become available. This step has a moderate technology forcing effect on NO_x control systems from diesel passenger cars. There is no expectation for the NO_x conformity factors to be tightened in the upcoming third RDE regulatory package. In-service conformity testing is also a political priority of the EC; however, it is more difficult to address from the legislator's perspective and likely to be met with resistance from industrial stakeholders. This issue is expected to be the focus of the fourth RDE regulatory package.
RDE+c	**Improvements in Key Areas 4 and 5 (expanded RDE boundaries, improved public access, further tightened CF)** The coverage of real-world driving conditions of the RDE test is extended, driving the adoption of advanced hardware solutions (e.g., combined LNT and SCR systems). The emissions under the previously uncontrolled driving conditions are decreased as a result (Key Area 4). Comprehensive monitoring of the fleet using inexpensive NO_x sensors and remote sensing almost completely eliminates the incidence of defeat devices and poor real-world calibrations (Key Area 5).	The expansion of the boundaries of the test procedure is likely to have significant technology-forcing effects (i.e., it will necessitate the adoption of advanced aftertreatment systems [hardware] and calibrations [software], which require appropriate lead time for industry to adjust). Further reductions in the CF are applied as a result of improvements on gaseous PEMS measurement technology (reduced uncertainty). The proposed improvements of RDE+c over RDE+b go beyond general expectations for the development of the RDE regulation.

2.2 REAL-WORLD NO$_x$ EMISSION FACTOR MODELING

A comprehensive database of 1-Hz on-road emissions data was used to estimate the real-world NO_x emission factors (EFs) from current (pre-RDE) Euro 6 diesel passenger cars and to project the real-world emission factors for RDE and RDE+ vehicles (Steps a to c). The emission factors represent average real-world NO_x emissions in milligrams per kilometer driven. A single value (covering a wide range of operating conditions) is estimated for each technology step. The emission factors are also expressed as a multiplier of the regulated Euro 6 emission limit for diesel passenger cars (80 mg/km over the type-approval NEDC test procedure—soon to be replaced by the Worldwide Harmonized Light Vehicles Test Procedure [WLTP]).

2.2.1   Emission factor components

The emission factors share the same main four components (with variable contributions to the overall emissions of each vehicle technology class):

[N] component (normal driving): This component reflects the emissions behavior during hot operation of the vehicles (e.g., after the cold-start event, or upon a hot

restart) and during conditions that could be qualitatively defined as "normal driving." They correspond with the driving conditions covered in the first two regulatory packages of the European RDE regulation (i.e., excluding cold start, unusually cold or hot ambient temperatures, aggressive driving, driving at high altitude, or DPF regeneration events). Under our modeling assumptions, approximately 80% of total vehicle kilometers traveled are expected to fall within normal driving,[5] whereas 8% of activity is expected to fall within cold-start conditions (see following section); the remaining ~12% of activity is expected to fall within "extended driving" conditions (see following section). Most Euro 6 vehicles are also expected to meet the applicable RDE NO$_X$ emissions limit (i.e., the nominal Euro 6 emission factor multiplied by a conformity factor) with a safety margin of 30%.

[C] component (cold-start): This component covers the emission behavior of the vehicles upon cold-engine start events. Cold-starting a diesel car leads to a period of elevated NO$_X$ emissions until the engine and the aftertreatment system reach their normal operating temperature ranges. For example, the NO$_X$ conversion in most SCR catalysts (a common NO$_X$ control technology for diesel passenger cars) drops dramatically below temperatures of 180–200°C. This emissions behavior should only affect the first few minutes of cold-started trips, but it can make up a significant share of total NO$_X$ emissions and related health impacts, especially if most trips in urban environments are relatively short and begin in cold-start conditions. Under our modeling assumptions, approximately 8% of total vehicle kilometers traveled are driven in cold-start conditions.[6]

[E] component (extended driving): This component is used to model the average emission behavior during driving conditions that lead to elevated NO$_X$ emissions (excluding cold-start events): unusually cold or hot ambient temperatures, aggressive driving, driving at high speeds, driving at higher altitude, and DPF regeneration events. A smaller share of total vehicle activity is expected to fall within this description (approximately 12% of total vehicle kilometers traveled). The NO$_X$ emissions behavior is expected to deteriorate significantly during "extended driving" conditions,[7] making this component a major contributor to overall NO$_X$ emissions. This pronounced increase in average emissions outside the "safe" operating area—which is largely determined by the regulated emissions test—is a key characteristic of the NO$_X$ emissions profile of modern diesel passenger cars.

[D] component (defeat devices): This component models the impact of defeat devices and poor emission control system calibrations on the average emissions behavior of the vehicle technology class. This component covers legally questionable defeat devices (e.g., driving cycle identification, "thermal windows" or "timer" defeat devices that switch off or modulate pollution-control systems during normal conditions of use; see Transport & Environment [2016]), and more "narrow" aftertreatment calibrations that cover only NEDC operating points, the latter being defended by the European automotive industry as legal due to the shortcomings of the NEDC type-approval framework and poor enforcement of defeat device provisions in the EU (Muncrief et al., 2016).

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5   The estimation of total vkm is not straightforward, because the boundary conditions of the RDE test are based on several parameters that include altitude, ambient temperature, road gradient (indirectly via a limit to cumulative altitude gain per distance driven over the trip), and driving dynamics. Driving at high altitude (between 700 and 1300 m above sea level) and at cold or hot ambient temperatures (between –2 to 3°C, or between 30 and 35°C) are only partially covered (even colder or hotter temperature intervals are excluded). The coverage of the RDE test was included in the uncertainty analysis described in Section 2.2.3.

6   This corresponds to a cold-start section of 2 km over a 25-km trip, which is consistent with the findings of Pasaoglu et al. (2012).

7   NO$_X$ formation in the engine is proportional to combustion temperature, which, in turn, is proportional to the load placed on the engine. Thus, harder acceleration rates and higher speeds will generate more NO$_X$ from the engine. Also, the proportion of exhaust gas recirculation that the engine can tolerate is reduced at higher engine loads, further increasing NO$_X$ formation in the engine.

2.2.2 Emission factor modeling rationale, main parameters, and assumptions

The emission factor modeling exercise integrates measured, on-road, 1-Hz NO_X emissions data from ICCT's PEMS database on Euro 6 diesel passenger cars with a number of expert assumptions on the evolution of real-world NO_X emission factors for the different emission factor components, as well as on the share of each component in the total vehicle kilometers traveled. The real-world NO_X emission factors for Euro 6 and later diesel passenger cars were modeled on the basis of PEMS data from 32 passenger cars certified to Euro 6 standards (Franco et al., 2014). The emission factors were derived with a conservative stance: for example, we chose to use the median instead of the mean to characterize the emissions behavior of the diesel Euro 6 cars in our database to avoid an undue influence of extreme outliers. Also, no deterioration factors were modeled. The calculated conformity factors from the data were 6.0 for cold starts and 7.6 for extended driving.[8] The normal driving conformity factor is assumed to be a function of the RDE conformity factor (currently 2.1) and a 30% safety margin. The defeat device conformity factor is the same as the conformity factor for extended driving (i.e., 7.6), but it is applied to the average emission factor (across all driving conditions) of vehicles assumed to use defeat devices (30% of the vehicles in ICCT's PEMS database). The derivation of the real-world diesel NO_X emission factors for the various scenarios is summarized in Table 2.

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8   The calculated CF of 7.6 for extended driving likely includes the impact of both higher engine loads and defeat strategies. However, under the current RDE program, these conditions are excluded from the RDE boundary conditions. Thus, manufacturers will not need to remove defeat strategies from extended driving under RDE and the calculated CF of 7.6 would still apply.

Table 2. Derivation of the real-world diesel NO$_X$ emission factors developed for the analysis.

Estimated EF	Rationale and derivation
Euro 5 and prior **800 mg/km**	This is the generic emission factor applicable to all driving situations for Euro 5 vehicles, consistent with Carslaw et al. (2011).
Pre-RDE **453 mg/km** **(5.7x Euro 6 limit)**	This is the generic EF applicable to all driving situations for pre-RDE Euro 6 vehicles (registered between 2012 and 2015). It is an average EF estimated from the ICCT PEMS database on Euro 6 diesel passenger cars. This EF is not modeled by components; instead, it is simply the median EF of the 32 Euro 6 diesel vehicles whose emissions are analyzed in Franco et al. (2014), where every vehicle is given equal weight. This emission factor is in line with other reports on the real-world NO$_X$ emissions from diesel passenger cars (Kadijk et al., 2015; Ligterink et al., 2013) and with the EFs from European emission inventory models such as COPERT or HBEFA, which put this EF at approximately 4.5 times the Euro 6 limit.
RDE **320±69 mg/km*** **(4.0x Euro 6 limit)**	This EF is modeled by the components described in Section 2.2.1: *[N] component*: The estimated EF achieved during the driving conditions covered by the RDE test is the Euro 6 limit multiplied by the applicable regulated CF (2.1), with a safety margin of 30% (consistent with best estimate of total uncertainty of RDE test produced by the European Commission (Directorate-General Joint Research Centre; EC-JRC). The "normal driving" EF is thus 2.1*0.7= 1.47x the Euro 6 limit. It applies to 80% of total vehicle-kilometers (vkm; excluding those covered by the [D] component). *[C] component*: For cold-start conditions, emissions are insufficiently controlled ("poor cold-start" EF of 6.0x Euro 6 limit). The poor cold-start EF is the median EF estimated from ICCT's PEMS database (32 Euro 6 diesel vehicles), where every vehicle is given equal weight. The cold-start EF for each vehicle is calculated as the average EF for all available cold-started trips considering the first 300 seconds of each trip (a simple criterion for cold-start event delimitation that is consistent with current RDE regulation). This EF applies to 8% of total vkm driven by RDE class vehicles (excluding those covered by the [D] component). *[E] component*: For extended driving conditions that are not fully covered by the RDE regulation (e.g., high load driving, high altitude, extended temperature ranges), emissions are poorly controlled ("poor extended" EF of 7.6x Euro 6 limit). The poor extended EF is calculated for each vehicle as the average windowed EF considering only the CO$_2$ windows with distance-specific NO$_X$ emissions higher than the 80th percentile for the vehicle (i.e., the average of the worse 20% of emissions). The generic EF is the median for 32 vehicles; this is applied to 12% of total vkm. *[D] component*: 30% of the fleet is assumed to have average emissions corresponding to the EF of the [E] component (uncontrolled/defeat device EF of 7.6x the Euro 6 limit). This EF applies over all vkm traveled by those vehicles assumed to be affected by defeat devices or poor emission-control calibrations. For comparison, the average EF of the 23 worst vehicles (out of 32 included in the analysis, i.e., 72%) is 7.2x.
RDE+a (cold start) **261±49 mg/km*** **(3.3x Euro 6 limit)**	This EF is modeled by the components described in Section 2.2.1: *[N] component*: No changes in assumptions from RDE. *[C] component:* NO$_X$ control is improved (improved cold-start EF is 2.5x Euro 6 limit) for cold-start conditions corresponding to 8% of total vkm driven by vehicles compliant with the RDE+a step. *[E] component:* No changes in assumptions from RDE. *[D] component*: The prevalence of defeat devices/poor calibrations is reduced to 20% of RDE+a vehicles (from 30% for RDE; the modeled prevalence of defeat devices/poor calibrations is still relatively high because the focus of RDE is not on defeat device detection).

Estimated EF	Rationale and derivation
RDE+b (tightened CF, in-service testing) **165±27 mg/km*** **(2.1x Euro 6 limit)**	This EF is modeled by the components described in Section 2.2.1: *[N] component*: The estimated EF achieved during the driving conditions covered by the RDE test is the Euro 6 limit multiplied by a tightened regulated CF (1.5), with a safety margin of 30% (normal driving EF is thus 1.5*0.7= 1.05x the Euro 6 limit). *[C] component:* Further improvement from RDE+a in proportion to the improvement of the [N] component. *[E] component:* No changes in assumptions from RDE. *[D] component*: Market surveillance and in-service conformity testing reduces the prevalence of defeat devices/poor calibrations from 20% to 5% (the largest absolute decrease in the prevalence of defeat devices/poor calibrations is modeled at this stage).
RDE+c (expanded RDE boundaries; improved public access, further tightened CF) **94±12 mg/km*** **(1.2x Euro 6 limit)**	This EF is modeled by the components described in Section 2.2.1: *[N] component*: The estimated EF achieved during the driving conditions covered by the RDE test is the Euro 6 limit multiplied by a further tightened regulated CF (1.2), with a safety margin of 30% (normal driving EF is thus 1.2*0.7= 0.84x the Euro 6 limit). *[C] component:* Further improvement from RDE+b in proportion to the improvement of the [N] component. *[E] component*: For driving conditions that are not fully covered by the baseline RDE on-road emissions test (e.g., high load driving, high altitude, extended temperature ranges), emissions control is improved (improved extended EF of 3.0x the Euro 6 limit). This reflects an average of conditions newly covered at the same CF as the normal component and conditions that continue to be excluded even from the extended conditions, for which the CF is unchanged. *[D] component*: Defeat device screening programs using remote sensing and on-board NO_x sensors further reduce the prevalence of defeat devices/poor calibrations from 5% to 1%.

*Uncertainties quoted correspond to the standard deviation of the EF populations derived from the Monte Carlo Simulation (see Section 2.2.3)

2.2.3 Emission factor uncertainty: Monte Carlo simulation

A simple Monte Carlo simulation was run to investigate the sensitivity of the modeled emission factors to variations in the input assumptions and their associated parameters, including the values of the emission factors estimated from the PEMS database, the shares of vehicle-kilometers (vkm) assigned to each emission factor component, and the estimated prevalence of defeat devices or poor NO_x control calibrations. All of the parameters were allowed to vary independently within a ±50% range using a pseudorandom number generator (rand function). A population of 1 million emission factors was iteratively produced for each one of the vehicle categories covered in. The means of the resulting emission factor populations converge strongly to the nominal emission factors, and their standard deviations provide insights into the margins of variability of the modeled emission factors as well as their sensitivities to the input parameters. A Matlab script is provided in Annex I that allows the results to be independently reproduced. Table 3 lists the emission factor modeling parameters that were randomly varied and their allowed ranges of variation.

Table 3. Emission factor modeling parameters used in the Monte Carlo simulation.

Parameter	Central estimate	Random range of variation (min.–max.)
Engineering safety margin for RDE test (% of regulated CF)	30%	15%–45%
Share of total vkm driven in cold-start condition (%)	8%	4%–12%
Share of total vkm driven in extended conditions (%)	12%	6%–18%
EF in cold-start condition (as multiplier of diesel Euro 6 limit)	RDE: 6.0 RDE+a: 2.5 RDE+b: 2.1 RDE+c: 1.7	RDE: 3.0–9.0 RDE+a: 1.25–3.75 RDE+b: 0.9–2.7 RDE+c: 0.7–2.1
EF in extended conditions (as multiplier of diesel Euro 6 limit)	RDE: 7.6 RDE+a: 7.6 RDE+b: 7.6 RDE+c: 3.0	RDE: 3.8–11.4 RDE+a: 3.8–11.4 RDE+b: 3.8–11.4 RDE+c: 1.5–4.5
EF in defeat device conditions (as multiplier of diesel Euro 6 limit)	All steps: 7.6	All steps: 3.8–11.4
Prevalence of defeat devices (% of vehicles in the class)	RDE: 30% RDE+a: 20% RDE+b: 5% RDE+c: 1%	RDE: 15%–45% RDE+a: 10%–30% RDE+b: 2.5%–7.5% RDE+c: 0.5%–1.5%

2.3 POLICY AND TECHNOLOGY SCENARIOS

We estimated NO$_X$ emissions and/or fleet average NO$_X$ emission factors from passenger cars in the 28 EU Member States (EU-28) under six pathways for the period 2015–2030 (Table 4). Emissions are estimated using a version of EMISIA SA's Sibyl model (EMISIA SA, 2016), modified to accommodate ICCT's real-world emission factor estimates for new diesel vehicles certified to Euro 4, Euro 5, Euro 6, RDE (Euro 6c), and subsequent RDE phases. For passenger cars fueled by gasoline and other (non-diesel) fuels, no changes were made to Sibyl's baseline of current policies and associated emission factors.

The first three scenarios focus on potential developments to the RDE program and its impacts on new diesel vehicle technology. The Baseline RDE pathway includes the currently adopted RDE program (first and second regulatory packages) for Euro 6c diesel cars but assumes no further improvements to the program. The Conservative RDE+ pathway assumes the implementation of cold-start provisions in 2020 followed by market surveillance and tightened conformity factors in 2023 (but no subsequent improvements). The Accelerated RDE+ pathway assumes the implementation of improvements in all five key areas on an accelerated implementation calendar, with the phase-ins of the different steps (mandatory dates of application for all new car registrations) taking place in 2018, 2020, and 2022 (Figure 4).

Table 4. Scenario definitions.

| Scenario	Description	Effect	Scope
Baseline RDE (reference fleet)	Includes the current adopted RDE program as of October 2015. Assumes no further RDE phases beyond the second regulatory package of RDE (European Commission, 2016b).[9] Assumes new diesel cars retain their current market share until 2030.	RDE and RDE+ programs drive improvements in real-world NO_X emissions from Euro 6 diesel passenger cars	EU-28
Conservative RDE+ (reference fleet)	Same as the previous scenario through 2019. From 2020–2022, all new diesel cars are certified to RDE+a (cold-start provisions). From 2023–2030, all new diesel cars are certified to the RDE+b step (adding market surveillance and tightened conformity factors). Assumes new diesel cars retain their current market share until 2030.		
Accelerated RDE+ (reference fleet)	Same as the previous scenario through 2017. From 2018–2019, all new diesel cars are certified to RDE+a. From 2020–2021, all new diesel cars are certified to RDE+b; finally, starting in 2022, all new diesel cars are certified to the RDE+c step (expanded test procedure boundaries, comprehensive fleet monitoring). Assumes new diesel cars retain their current market share until 2030.		
Baseline RDE (market shift)	Two sensitivity scenarios model a decline in new diesel car market share from approximately 50% in 2016 to less than 20% in 2030, with gasoline cars capturing the market share lost by diesel cars. The assumed steady decline in diesel market share is equivalent to a 1 to 3 percentage point drop in market share each year. These assumptions are added to the Baseline RDE and Accelerated RDE+ scenarios.	A gradual market share decline for diesel passenger cars (displaced by gasoline) further reduces fleet-average real-world NO_X emissions	
Accelerated RDE+ (market shift)			
LEZ	Sensitivity scenarios model the impacts of an LEZ implemented in a city with EU-average fleet technology mix. Minimum emission certification level requirements tighten from Euro 3 (diesel) and Euro 2 (gasoline) in 2020 to a minimum of Euro 6c (diesel) and Euro 4 (gasoline) in 2026.	Restrictions on the activity of vehicle classes with higher NO_X emissions accelerate fleet renewal	Local
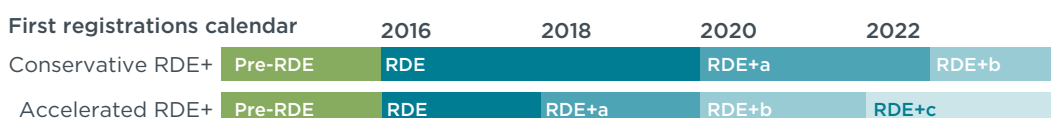
Figure 4. Timeline for improvement of RDE program under the Conservative RDE+ and Accelerated RDE+ scenarios.

Next, we evaluate two scenarios that build off of the Baseline RDE and Accelerated RDE+ pathways, assuming a decline in the market share of new diesel cars across the EU. In contrast to the reference case for vehicle activity (used for the first three RDE policy pathways), which assumes that diesel cars retain their market share (EMISIA SA, 2016), the market shift scenarios assume that new diesel cars lose 1 to 3 percentage points in market share per year, declining to less than 20% of new car registrations in 2030. Gasoline-fueled cars are assumed to capture the market share lost by diesel cars. Such a shift could be driven by a combination of factors, for example, shifting consumer sentiment regarding the environmental performance of diesel cars, changes in new vehicle registration fees or fuel excise taxes, or an increase in emission control costs for diesel cars related to tightened RDE regulations. Although such policies or shifts in consumer preferences could contribute to a decrease in the market share of diesel cars, we do not attempt to quantify the market impacts of any specific factor; rather, we evaluate the potential EU-wide NO_X emissions impacts of a hypothetical decline in the market share of diesel passenger cars to better understand the need for a strengthened RDE program to control NO_X emissions.

9 The Baseline RDE scenario (i.e., no further RDE development beyond what is currently approved) is very unlikely to materialize, as the RDE regulation is expected to be completed by at least two further regulatory packages (third and fourth RDE regulatory packages). The third RDE regulatory package is currently being finalized by the European Commission, and its publication is expected in the first half of 2017.

In contrast to the first five scenarios, the LEZ scenario is applicable at the local level rather than the regional (EU) level. This scenario builds off of the three modeled pathways for the RDE program (including Baseline RDE), evaluating the potential impacts of an LEZ (or environment zone) implemented in a city with a passenger car fleet technology mix similar to the EU-28 average. Taking into account the design of existing LEZs in various European cities, this LEZ is assumed to phase in from 2020 to 2026 and require vehicles to meet a minimum emission certification level in order to enter the city. The modeled program would require a minimum of Euro 3 for diesel cars and Euro 2 for gasoline cars in 2020, progressively tightening to a minimum of Euro 6c (current RDE) for diesel cars and Euro 4 for gasoline cars in 2026 (although not evaluated in this analysis, a more advanced LEZ could eventually aim to limit activity to plug-in hybrid or zero-emission vehicles). Because the absolute emissions benefits would be determined by the scale of the program and the specific passenger car technology mix, results for this scenario instead focus on the share of passenger car activity by technology and the fleet average NO$_X$ emission factor over time.

3. RESULTS AND DISCUSSION

The diesel emissions scandal has brought the real-world diesel NO_x issue to the mainstream. Recent testing performed by the governments of Germany, the Netherlands, France, and the United Kingdom and by independent organizations (including the ICCT) has helped delineate the problem of real-world NO_x emissions from diesel passenger cars. An overwhelming amount of experimental evidence points to a severe noncompliance problem that concerns not only Volkswagen, but rather affects the vast majority of diesel passenger cars certified to the Euro 5 and Euro 6 standards (i.e., the technology classes that will dominate the emissions behavior of EU fleets in the coming years).

We carefully built two policy pathways with different levels of ambition (Conservative RDE+ and Accelerated RDE+) and modeled the real-world NO_x emission factors for the corresponding regulatory steps. We phased in the various technical improvements to the Baseline RDE regulation according to a calendar that takes into consideration the current work of the RDE group and the technical challenges facing car manufacturers and regulators. For example, we placed the improved control of cold-start emissions—which will be covered in the third regulatory package of RDE, and which we think is technically achievable within a short time frame—as a short-term priority, and allowed more lead time for substantive changes (e.g., planning the expansion of the driving conditions covered by the RDE test for 2022 would give industry sufficient time to start engineering improved NO_x aftertreatment hardware, such as combined LNT and SCR systems).

Despite the uncertainties surrounding several aspects of our modeling exercise (namely the prevalence of defeat devices/poor real-world calibrations in diesel Euro 6 cars and the evolution of the market share of diesel cars in the EU), our work provides insights into the effects of plausible scenarios on real-world NO_x emissions of the EU passenger car fleet.

3.1 RDE AND RDE+: REAL-WORLD NO_x EMISSION FACTORS

The main results of the real-world NO_x emission factor modeling exercise are captured in Figure 5. Following from our input assumptions, properly calibrated Euro 6 diesel passenger cars should be able to have real-world emissions behavior in line with the Euro 6 limit of 80 mg/km if only normal driving (i.e., the relatively undemanding conditions covered by the current RDE test) emissions are taken into account. But the real-world Baseline RDE emission factor increases to just over twice the Euro 6 limit once the effects of cold-start and extended driving are included. This effect is further amplified by the contribution of the share of the fleet assumed to have defeat devices or poor NO_x control calibrations, which effectively double the real-world emission factor and put it at its overall estimated value of 4 times the Euro 6 limit.
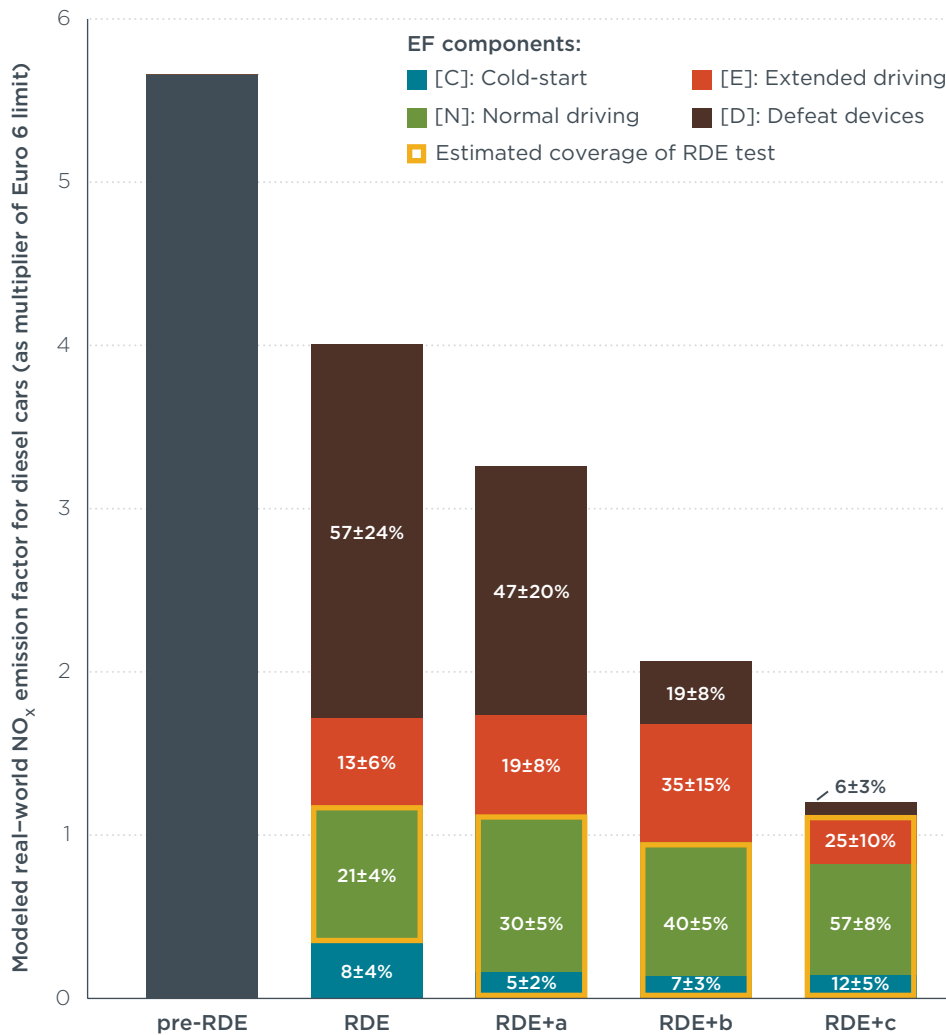
Figure 5. Modeled real-world diesel NO$_X$ emission factors for RDE and later vehicle classes (percentage contributions of each component indicated within the stacked bars; error margins are standard deviations of emission factor component populations resulting from the Monte Carlo analysis).

The incorporation of cold-start to the regulated RDE test brings significant improvements to the real-world emission factor of the RDE+a class, but the largest reduction comes from the expected drop in the prevalence of defeat devices/poor calibrations among new vehicle registrations. This reduction is most pronounced for the RDE+b and RDE+c steps, which include specific policies to eradicate these practices (e.g., in-service conformity testing for RDE+b and comprehensive fleet screening using on-board NO$_X$ sensors and remote sensing for RDE+c). If the RDE+c policy step is adopted, the defeat device component of the emission factor is expected to be minimal.

The importance of the extended driving emission factor component grows both in relative and absolute terms from RDE to RDE+b, where it experiences a peak and dominates the real-world emission factor (relative contribution of 35±15%). This behavior is explained by the substitution of defeat device activity with extended driving activity (still with relatively poor emissions behavior). The emissions behavior under extended driving is expected to improve only after the coverage of the RDE test is expanded with the introduction of the RDE+c step. After this milestone, the real-world diesel NO$_X$ emission factor is reduced by approximately 43% from RDE+b, and the contribution of normal driving exceeds the sum of contributions by the other emission factor

components for the first time (even though the vast majority of vehicle-kilometers are consistently assumed to be driven in normal conditions).

Figure 6 compares the development of real-world NO_x emission factors for diesel and gasoline passenger cars with regulated emission limits. Emission factors for diesel cars certified to Euro 1 through Euro 3 and gasoline cars certified to Euro 1 through Euro 6 are based on Sibyl defaults. Real-world emission factors for diesel cars certified to Euro 6 (pre-RDE) standards are median estimates from ICCT's PEMS database. Emission factors for diesel cars under the current RDE program (Euro 6c) and future RDE+ steps are modeled according to the methods in the preceding section. Since NO_x-specific emission limits were introduced for Euro 3 cars, real-world emissions from diesel cars have exceeded regulated emission limits, while gasoline cars have performed within their regulated emission limits (NO_x and hydrocarbons [HC] were regulated together for Euro 1 and Euro 2, thus no NO_x-specific emission limits are shown in the chart for these standards). On average, diesel cars certified to Euro 4, Euro 5, and Euro 6 (pre-RDE) standards emit approximately 3.2, 4.4, and 5.7 times their respective regulated emission limits.

The error bars for Euro 5 diesel cars reflect the range of results of PEMS studies conducted in France, Germany, and the United Kingdom as reported in Ntziachristos et al. (2016a). Error bars for Euro 6 diesel cars at various stages of RDE are drawn from the Monte Carlo analysis described in the previous section. Although these error bars illustrate the uncertainty in emission factors related to the prevalence of defeat devices and coverage of the RDE test, among other factors, only the central estimates were applied in the fleet emissions modeling.
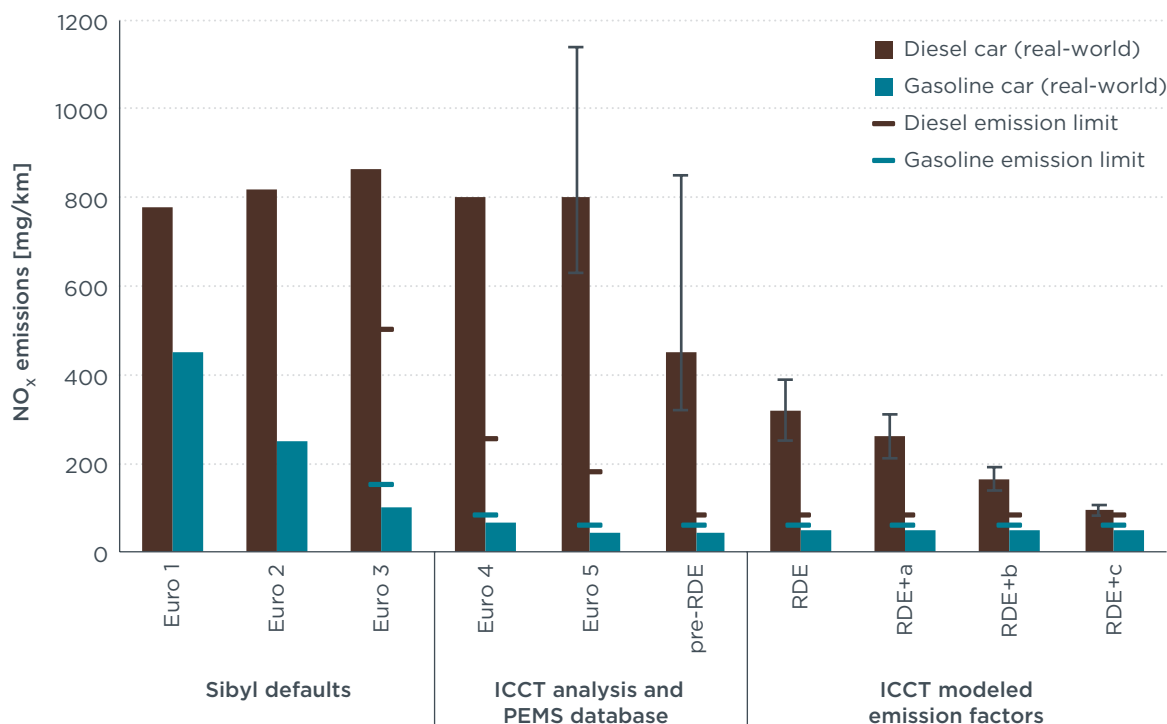
Figure 6. Passenger car real-world NO_x emission factors versus regulatory emission limits.

3.2 NEW PASSENGER CAR REGISTRATIONS, STOCK, AND ACTIVITY

Figure 7 indicates the projected share of new passenger car registrations in the EU by vehicle and fuel type under the reference (common to RDE and RDE+ projections) and market shift scenarios. As discussed previously, the reference case assumes that diesel cars will continue to account for about half of new passenger car registrations though

2030. The first three RDE scenarios do not assume any changes in fuel mix from the reference case, instead focusing on the emissions impacts of new diesel technologies given this projected fuel mix. In contrast, the market shift scenarios examine the emissions impact of a decline in the market share of new diesel passenger cars in combination with the Baseline RDE or Accelerated RDE+ scenarios, respectively. Battery electric, plug-in hybrid, and fuel cell vehicles are included in the Gasoline Hybrid & Electrified category shown in Figure 7.
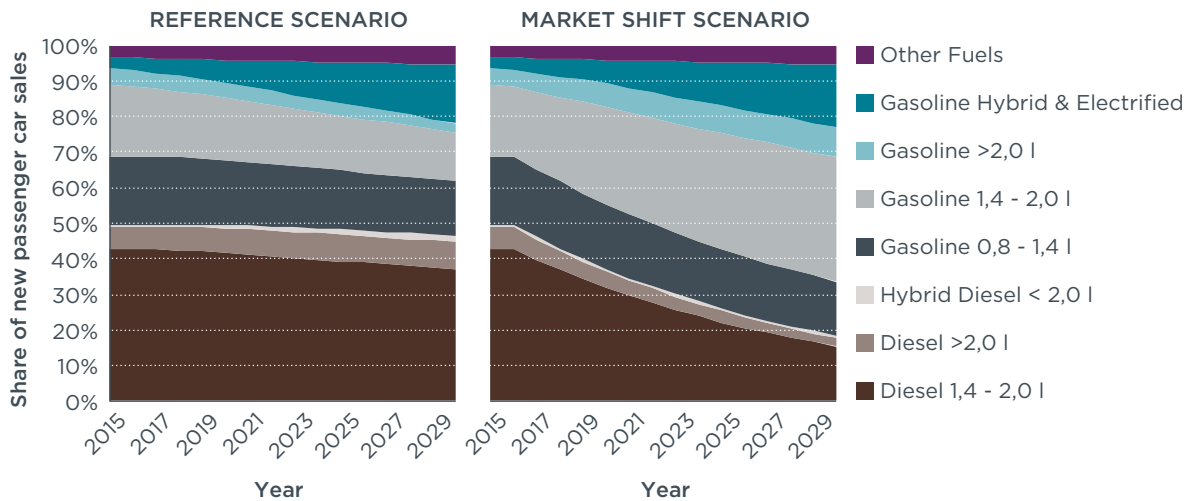
Figure 7. New passenger car registrations by vehicle and fuel type, 2015–2030.

The reference case projects that diesel cars will make up 50% of the passenger car fleet across the EU-28 in 2030, compared to approximately 5% for gasoline hybrids, 7% for cars fueled by compressed natural gas (CNG) or liquefied petroleum gas (LPG), and less than 1.5% for zero-emission vehicles (defined as vehicles having zero tailpipe emissions, i.e., battery electric and fuel-cell vehicles; Figure 8). Under the market shift scenarios, we estimate that even if diesel cars steadily lose popularity, they could still account for approximately 40% of the passenger car fleet in 2030.
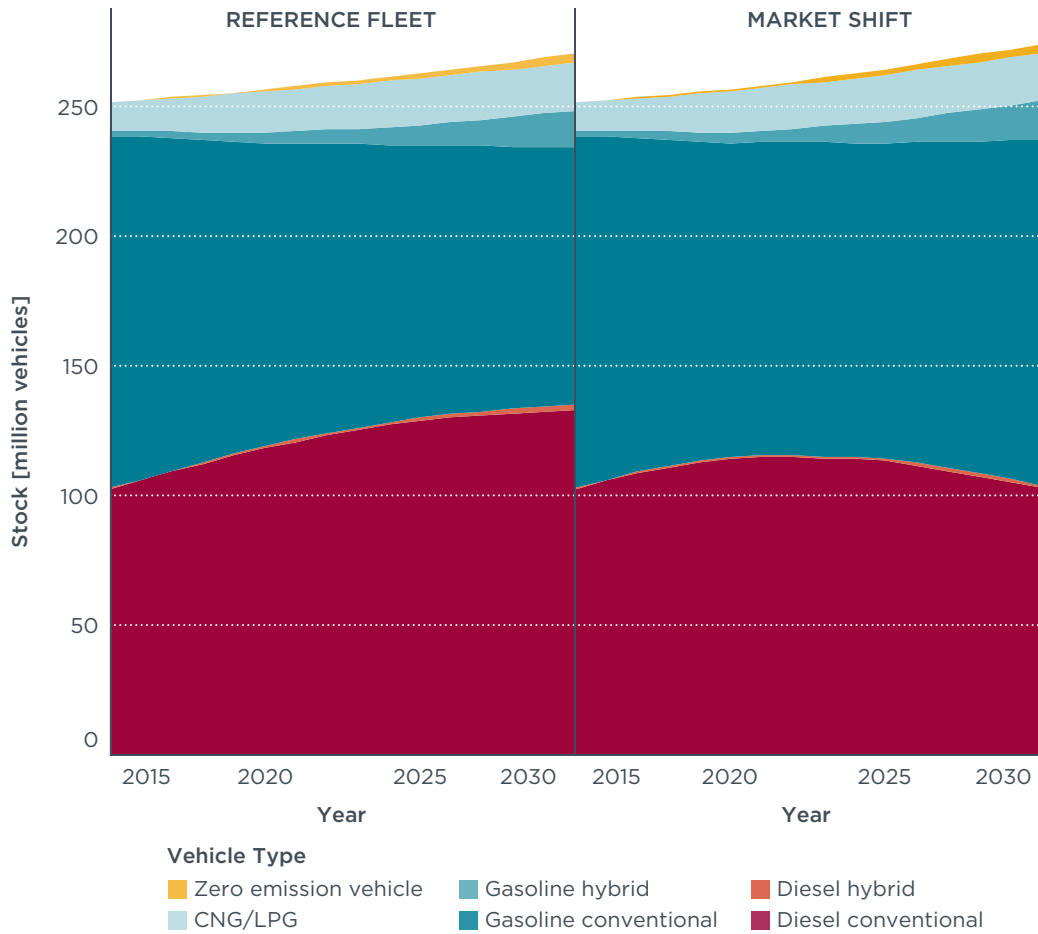
Figure 8. Passenger car stock in the EU-28 by fuel type, 2015–2030.

Figure 9 shows the potential development of the passenger car fleet under the three RDE scenarios (reference fuel mix) and the two market shift scenarios, which are overlaid on Baseline RDE and Accelerated RDE+. According to the rate of fleet turnover and fuel mix in the reference case, by 2030 approximately one third of the passenger car fleet will consist of diesel cars first registered after 2016. These cars will emit NO_x at levels consistent with RDE (Euro 6c), RDE+a, RDE+b, or RDE+c, depending on the RDE scenario considered. Notably, the main difference between the reference and market shift scenarios is that there would be fewer diesel cars meeting the latest standard (i.e., RDE or RDE+c), because most of the assumed reduction in diesel car sales occurs after 2022.
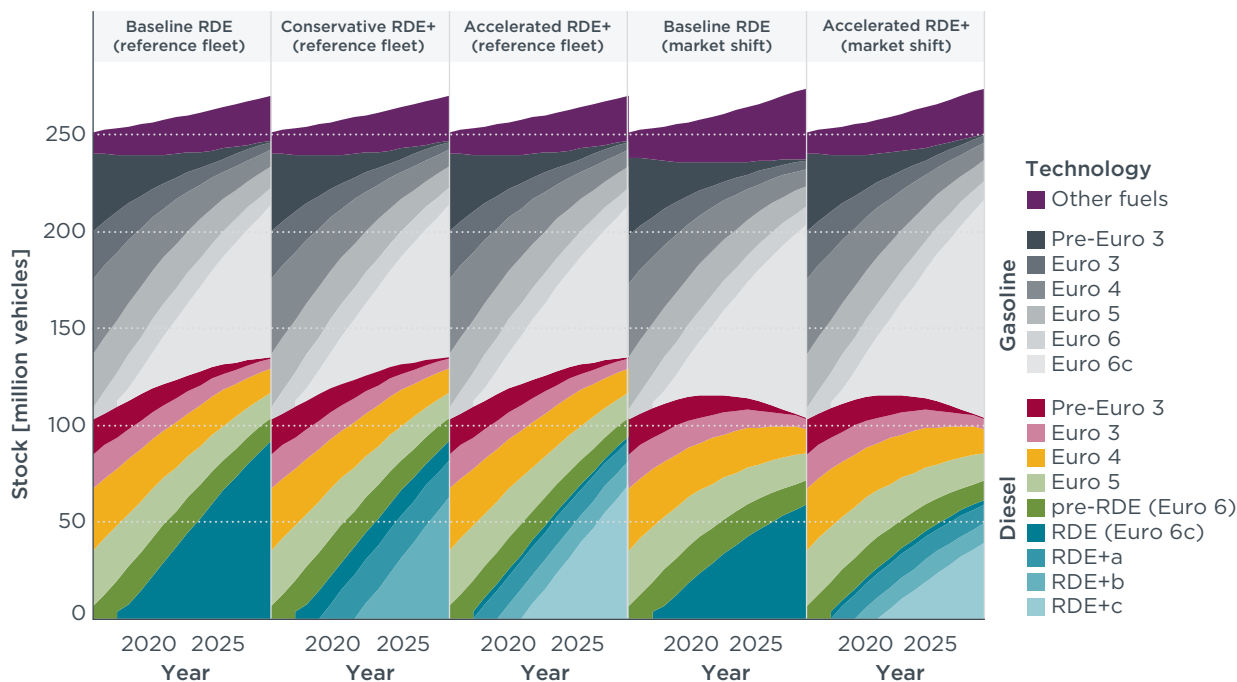
Figure 9. Passenger car stock in the EU-28 by vehicle technology, 2015–2030.

Figure 10 illustrates a similar trend as the previous figure, showing projected vehicle-kilometers traveled by passenger cars in the EU-28 by vehicle technology. In 2030, the reference case projects that diesel cars will account for 50% of the passenger car fleet and 60% of passenger car activity, reflecting the tendency of diesel cars to have higher annual mileage than those fueled by gasoline. Likewise, diesel cars sold after 2016 are projected to account for a third of the passenger car fleet but nearly half of passenger car activity in 2030, reflecting the tendency of newer cars to have higher annual mileage than older cars.
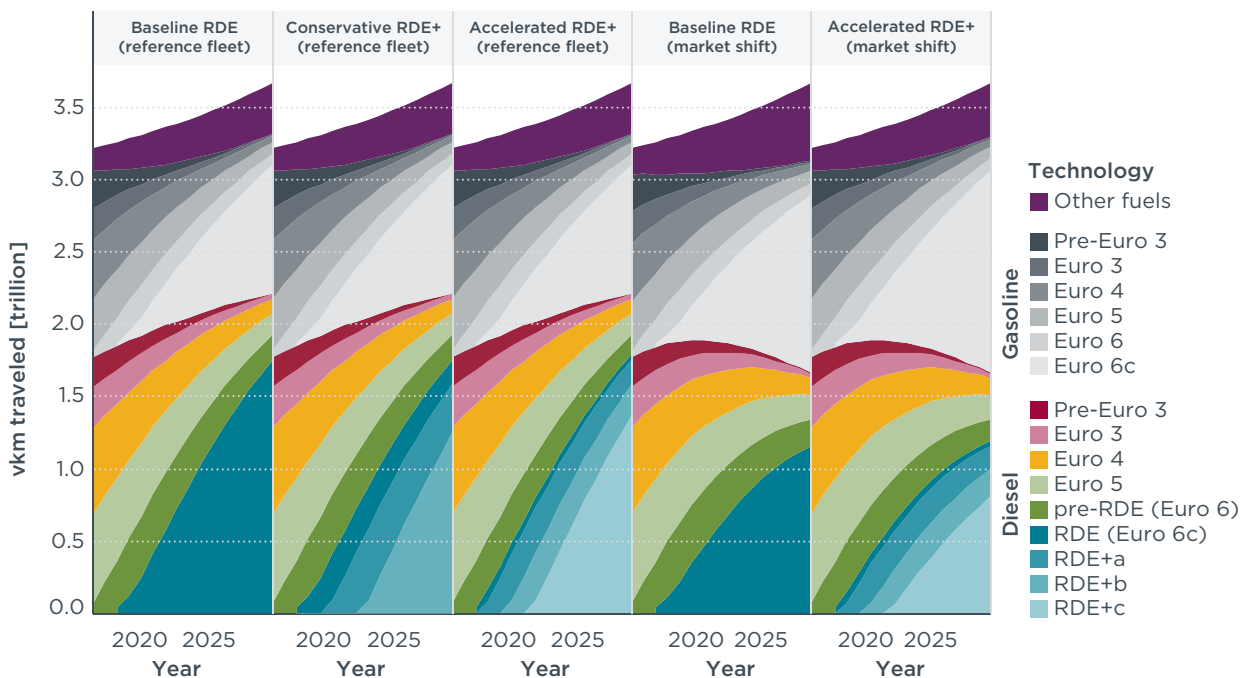
Figure 10. Passenger car activity in the EU-28 by vehicle technology, 2015–2030.

3.3 PROJECTED PASSENGER CAR NO$_X$ EMISSIONS IN THE EUROPEAN UNION

Figure 11 indicates the potential impact of each policy and technology pathway on the development of passenger car NO$_X$ emissions in the EU-28 from 2015 to 2030. Whereas diesel cars accounted for approximately 50% of the passenger car fleet across the EU-28 in 2015, they contributed more than 80% of passenger car NO$_X$ emissions. This percentage increases in the future as older gasoline cars with higher NO$_X$ emissions are retired from the fleet. In each scenario, diesel Euro 4 and Euro 5 cars dominate NO$_X$ emissions in the first few years after 2015, and Euro 6 diesel cars dominate by the year 2030. Fleetwide NO$_X$ emissions are expected to be lower in 2030 than in 2015 as a result of older vehicles being replaced by newer ones with lower average absolute NO$_X$ emissions. For the RDE scenarios with reference market share, this reduction in fleetwide NO$_X$ ranges from 46% under the current RDE program (Baseline RDE) to 67% in the Accelerated RDE+ scenario. In absolute terms, the Conservative RDE+ scenario could reduce passenger car NO$_X$ emissions in the EU-28 by 210,000 metric tons in 2030 compared to the Baseline RDE, versus a reduction of 360,000 metric tons under the Accelerated RDE+ scenario. Even with a substantial decline in the market share of diesel cars (Market shift), the Accelerated RDE+ program would still reduce 210,000 tons of NO$_X$ per year in 2030 compared to the Baseline RDE. This finding indicates that an ambitious RDE program (i.e., Accelerated RDE+) is essential to control NO$_X$ from passenger cars even if the market share of new diesel cars were expected to decline. Moreover, an improved RDE program would reduce the sensitivity of passenger car NO$_X$ emissions to market trends, enabling environmental regulators to have greater confidence in planned air quality improvements.
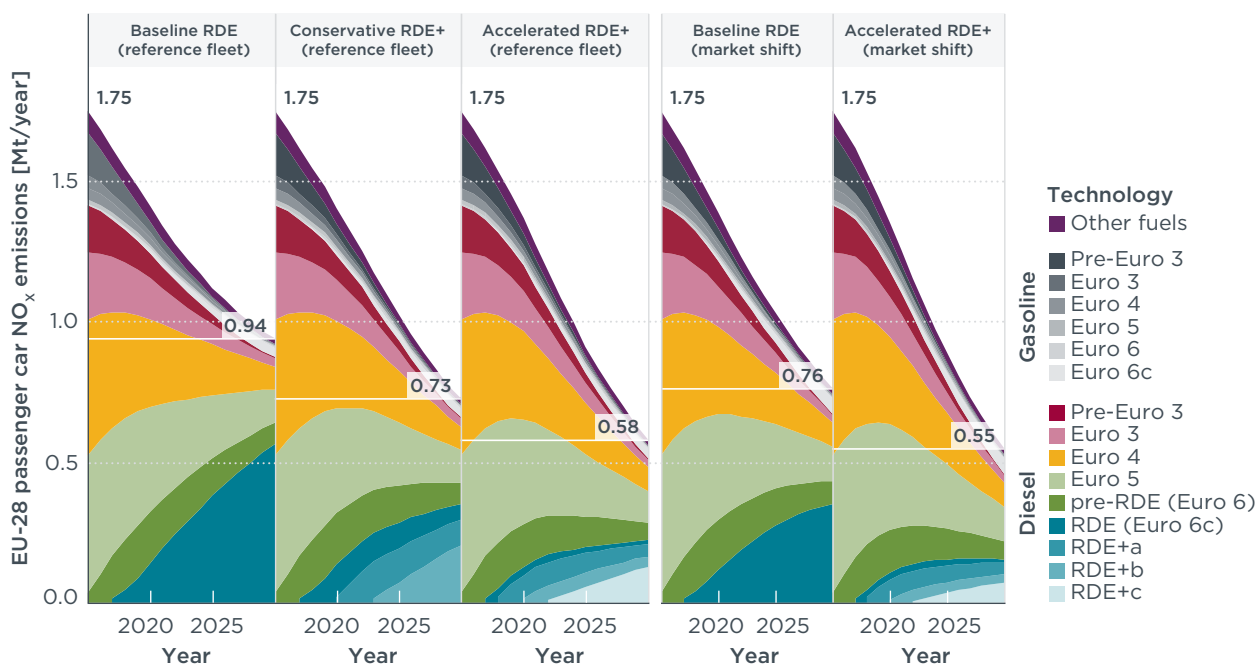
Figure 11. Passenger car NO$_X$ emissions in the EU-28 by vehicle technology, 2015–2030.

The impact of further developments to the RDE program can also be framed in terms of the percent reduction in passenger car NO$_X$ emissions in 2030 compared to the current program. As illustrated in Figure 12, the (reference fleet) Conservative RDE+ and Accelerated RDE+ scenarios would reduce NO$_X$ emissions by 23% and 38%, respectively, compared to the Baseline RDE in 2030.
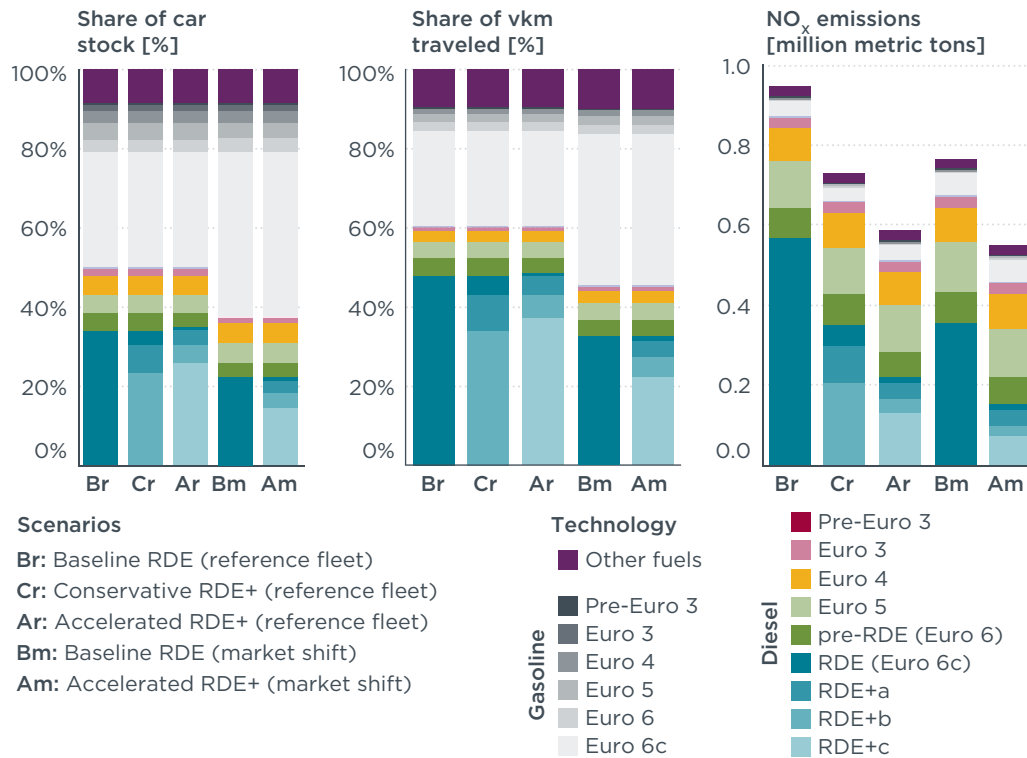
Figure 12. Passenger car stock, activity, and NO$_X$ emissions in the EU-28 by vehicle technology, 2030.

In addition to absolute impacts on vehicle stock, activity, and NO$_X$ emissions, the results of these policy scenarios can be conceptualized in terms of fleet average NO$_X$ emission factors. Expressed in grams per vehicle-kilometer traveled, these factors reflect the current and projected composition of the passenger car fleet by vehicle and fuel type (Figure 13). In 2015, the average passenger car in the EU-28 emitted an estimated 550 mg/km of NO$_X$, equivalent to 6.9 times the Euro 6 limit for diesel cars and more than 9.1 times the Euro 6 limit for gasoline cars. In the same year, the average diesel passenger car emitted 4 times as much NO$_X$ per vehicle-kilometer as the average gasoline passenger car. Under the Baseline RDE scenario, by 2030, the average diesel car would emit 7.7 times as much NO$_X$ per vehicle-kilometer as the average gasoline car. Under the Conservative RDE+ and Accelerated RDE+ scenarios, this multiplier would decline to 5.8 and 4.5 times, respectively.

Because the market shift scenarios assume a declining market share of new diesel cars, fleet average diesel car emission factors would improve more slowly than in the reference scenarios due to a smaller number of new diesel cars (subject to RDE or RDE+, and hence with lower emissions than the average Euro 4, Euro 5, or Euro 6 pre-RDE diesel car) entering the fleet. This effect can be observed by comparing the fleet average diesel car emission factors in 2030 in the third and fifth panels of Figure 13, titled Accelerated RDE+ (reference fleet) and Accelerated RDE+ (market shift).

The reference case estimates that passenger cars fueled by CNG/LPG emitted more NO$_X$ per vehicle-kilometer in 2015 than did gasoline cars, but that these emission factors will be similar to gasoline cars by 2030 (a decline of approximately 85% from 2015 to 2030). The share of activity by zero-emission vehicles is taken into account in the fleet average emission factor.
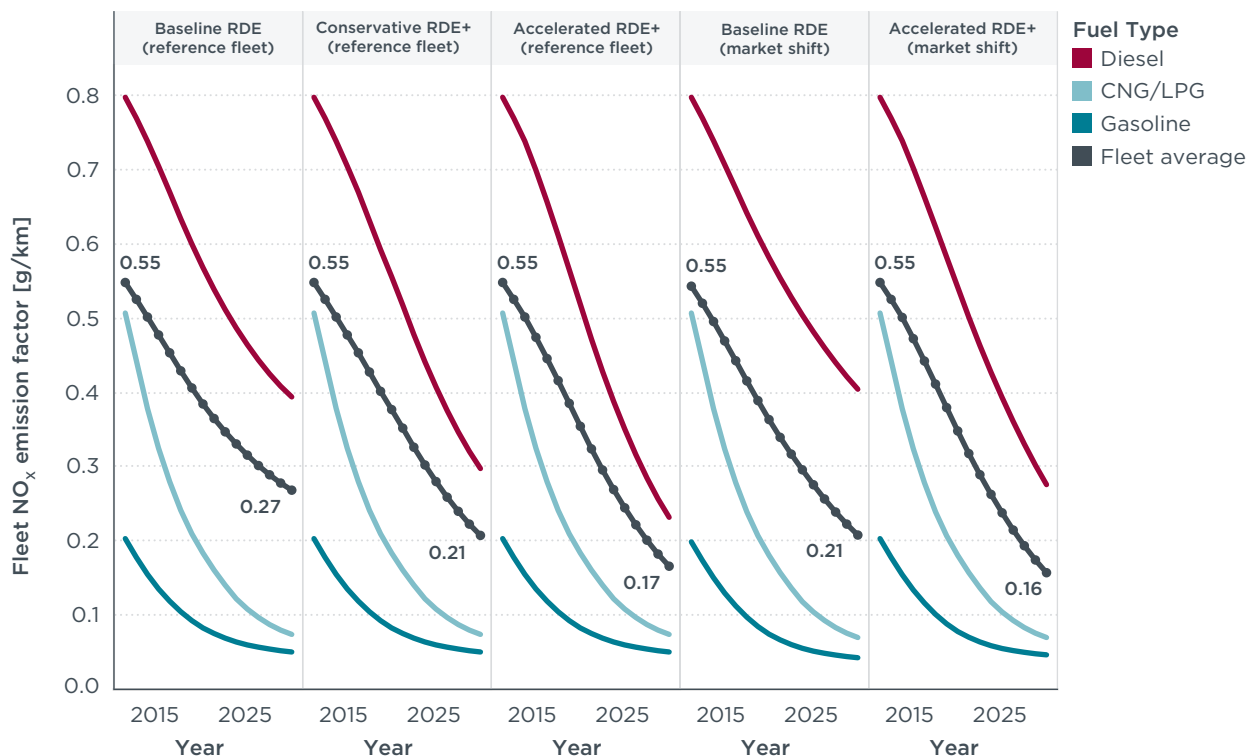
Figure 13. Fleet average passenger car NO$_X$ emission factors by fuel type, 2015–2030.

3.4 FLEET AND NO$_X$ EMISSION IMPACTS OF A REPRESENTATIVE LEZ

As regulators aim to bring new diesel car NO$_X$ emissions in line with emission limits, many cities with pressing air-quality issues are moving to limit the activity of higher emitting vehicles to reduce emissions from the in-use fleet. These city-level restrictions include congestion charges, weekday travel bans based on emission certification, and LEZs (also called "environment zones"). Germany has a national emission-labeling scheme that assigns window stickers based on fuel type and emission certification level. As of 2016, LEZs have been implemented extensively across Germany, with most participating cities restricting entry to vehicles with a green Phase 4 sticker (Umwelt Bundesamt, 2016). To qualify for a Phase 4 sticker, diesel cars must be certified to Euro 4 or later (or Euro 3 with a DPF retrofit); requirements for gasoline cars are significantly less stringent, requiring Euro 1 certification or a catalytic converter retrofit (European Commission, 2015).

Other European cities have taken actions to similarly limit activity by older vehicles, especially diesels. London's Ultra Low Emission Zone imposes a daily charge on gasoline cars not certified to Euro 4 or better and diesel cars not certified to Euro 6 or better (Transport for London, 2016). Similarly, Paris has announced plans to ban weekday travel by diesel passenger cars older than 2011 (corresponding to the introduction of Euro 5a) by 2020 (Chazan, 2016).

Following from our evaluation of the three policy pathways for new diesel car technology, an emission-control program targeting new vehicles alone will not be as effective as a program that combines lower emitting new vehicles with measures to control in-use vehicle emissions—thereby limiting the activity of older, higher emitting vehicles while concurrently requiring new vehicles to be equipped with more effective emission controls. Because most of the existing LEZs in Europe have been implemented at the local level (supported by a national vehicle-labeling scheme in Germany, for example), we quantified the potential impacts of a combined program

(future RDE phases plus an LEZ) for a hypothetical average EU city (in terms of fleet technology mix) rather than at the national or EU level.

Table 5 summarizes the minimum emission standard requirements for an LEZ, which are assumed to be phased in from 2020 to 2026. These requirements include a minimum of Euro 3 for diesel cars and Euro 2 for gasoline cars in 2020, progressively tightening to require a minimum of Euro 6c (current RDE) for diesel cars and Euro 4 for gasoline cars in 2026. Based on the historical timeline for the introduction of European emission standards, this LEZ would effectively restrict entry to diesel cars older than approximately 19 years and gasoline cars older than 22 years in 2020, tightening to a maximum age of 8 years for diesel cars and 20 years for gasoline cars in 2026. By phasing in progressively but predictably, such a program would allow consumers to adapt their purchases based on the expected phase-in: for example, buyers of a Euro 6 diesel car in 2016 could expect to operate the car for 10 years before it would be restricted from entering the LEZ (after which, it would presumably be sold and driven outside the LEZ). Although a more aggressive LEZ could aim to eventually limit activity to plug-in hybrid and zero-emission vehicles, this analysis demonstrates the significant benefits of a more conservative program focused on progressively eliminating the highest emitting vehicles.

Table 5. Minimum emission standard certification for an LEZ.

Fuel type	Year			
	2020	**2022**	**2024**	**2026**
Diesel	Euro 3	Euro 5	Euro 6	RDE (Euro 6c)
Gasoline	Euro 2	Euro 3	Euro 4	

In modeling the impacts of an LEZ on passenger car activity, we assumed that any activity by restricted vehicles (not meeting the requirements of the zone) is replaced by the least costly eligible vehicle technology. Figure 14 illustrates these shifts in passenger car activity with introduction of an LEZ in conjunction with the Accelerated RDE+ program for new diesel car technology. As indicated, vehicle-kilometers traveled by pre-Euro 3 diesel cars would be replaced with activity by Euro 2 gasoline cars in 2020. In 2022, this activity would shift to Euro 3 gasoline cars, then in 2024, to Euro 4 gasoline cars in accordance with the LEZ requirements. By the time the LEZ is fully phased in (2026), all permitted passenger car activity would be in diesel cars meeting some form of RDE and gasoline cars certified to Euro 4 or better. The share of passenger car activity by technology with and without an LEZ is summarized in Figure 15.
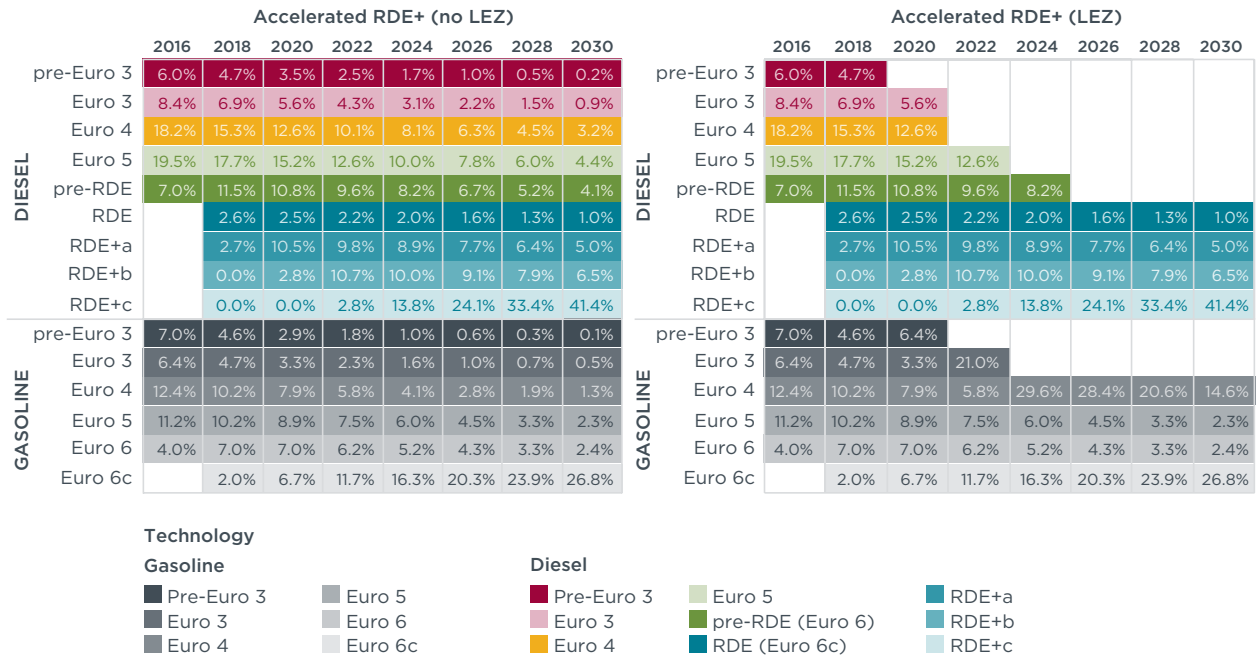
Accelerated RDE+ (no LEZ)

		2016	2018	2020	2022	2024	2026	2028	2030
DIESEL	pre-Euro 3	6.0%	4.7%	3.5%	2.5%	1.7%	1.0%	0.5%	0.2%
	Euro 3	8.4%	6.9%	5.6%	4.3%	3.1%	2.2%	1.5%	0.9%
	Euro 4	18.2%	15.3%	12.6%	10.1%	8.1%	6.3%	4.5%	3.2%
	Euro 5	19.5%	17.7%	15.2%	12.6%	10.0%	7.8%	6.0%	4.4%
	pre-RDE	7.0%	11.5%	10.8%	9.6%	8.2%	6.7%	5.2%	4.1%
	RDE		2.6%	2.5%	2.2%	2.0%	1.6%	1.3%	1.0%
	RDE+a		2.7%	10.5%	9.8%	8.9%	7.7%	6.4%	5.0%
	RDE+b		0.0%	2.8%	10.7%	10.0%	9.1%	7.9%	6.5%
	RDE+c		0.0%	0.0%	2.8%	13.8%	24.1%	33.4%	41.4%
GASOLINE	pre-Euro 3	7.0%	4.6%	2.9%	1.8%	1.0%	0.6%	0.3%	0.1%
	Euro 3	6.4%	4.7%	3.3%	2.3%	1.6%	1.0%	0.7%	0.5%
	Euro 4	12.4%	10.2%	7.9%	5.8%	4.1%	2.8%	1.9%	1.3%
	Euro 5	11.2%	10.2%	8.9%	7.5%	6.0%	4.5%	3.3%	2.3%
	Euro 6	4.0%	7.0%	7.0%	6.2%	5.2%	4.3%	3.3%	2.4%
	Euro 6c		2.0%	6.7%	11.7%	16.3%	20.3%	23.9%	26.8%

Accelerated RDE+ (LEZ)

		2016	2018	2020	2022	2024	2026	2028	2030
DIESEL	pre-Euro 3	6.0%	4.7%						
	Euro 3	8.4%	6.9%	5.6%					
	Euro 4	18.2%	15.3%	12.6%					
	Euro 5	19.5%	17.7%	15.2%	12.6%				
	pre-RDE	7.0%	11.5%	10.8%	9.6%	8.2%			
	RDE		2.6%	2.5%	2.2%	2.0%	1.6%	1.3%	1.0%
	RDE+a		2.7%	10.5%	9.8%	8.9%	7.7%	6.4%	5.0%
	RDE+b		0.0%	2.8%	10.7%	10.0%	9.1%	7.9%	6.5%
	RDE+c		0.0%	0.0%	2.8%	13.8%	24.1%	33.4%	41.4%
GASOLINE	pre-Euro 3	7.0%	4.6%	6.4%					
	Euro 3	6.4%	4.7%	3.3%	21.0%				
	Euro 4	12.4%	10.2%	7.9%	5.8%	29.6%	28.4%	20.6%	14.6%
	Euro 5	11.2%	10.2%	8.9%	7.5%	6.0%	4.5%	3.3%	2.3%
	Euro 6	4.0%	7.0%	7.0%	6.2%	5.2%	4.3%	3.3%	2.4%
	Euro 6c		2.0%	6.7%	11.7%	16.3%	20.3%	23.9%	26.8%

Technology

Gasoline
- Pre-Euro 3
- Euro 3
- Euro 4
- Euro 5
- Euro 6
- Euro 6c

Diesel
- Pre-Euro 3
- Euro 3
- Euro 4
- Euro 5
- pre-RDE (Euro 6)
- RDE (Euro 6c)
- RDE+a
- RDE+b
- RDE+c

Figure 14. Shifts in share of passenger car activity by technology with LEZ, Accelerated RDE+ scenario.
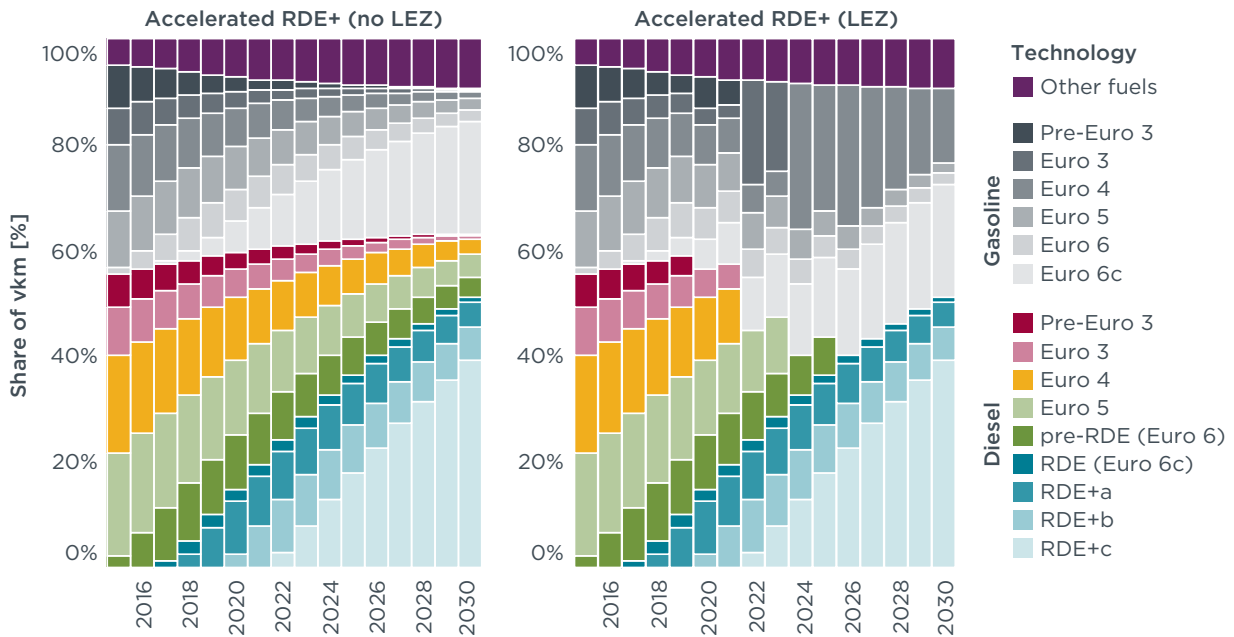

Figure 15. Share of passenger car activity by technology with LEZ, Accelerated RDE+ scenario.

For cities implementing an LEZ in conjunction with an EU-wide program to lower new diesel car emissions, the fleet-wide NO_x emissions benefits would be substantial. Figure 16 illustrates the average NO_x emission factor for passenger cars, expressed as a multiplier of the Euro 6 diesel NO_x limit of 80 mg/km.[10] Results are shown for each of the three RDE policy scenarios, with and without introduction of an LEZ. Whereas in 2015 the average passenger car in the EU emitted 6.9 times the Euro 6 diesel limit, the average passenger car in 2030 would emit half that level under the current RDE program (Baseline RDE, no LEZ). In contrast, the Conservative RDE+, no LEZ and

10 To derive the absolute emission factor, multiply by the Euro 6 limit of 80 mg/km.

Accelerated RDE+, no LEZ scenarios would reduce average passenger car emissions to 2.6 and 2.1 times the Euro 6 diesel limit by 2030, respectively.

Implementing an LEZ with the current RDE program (Baseline RDE, LEZ) would reduce the fleet average NO$_X$ emission factor through 2026, after which this emission factor would begin to increase. The low point corresponds to the year when all pre-RDE Euro 6 diesel cars would be removed from the fleet, and very few diesel cars would be left (those meeting the current RDE program); the subsequent emission factor increase results from sales of RDE diesel cars that still emit approximately 4 times the Euro 6 diesel NO$_X$ limit, which would actually be higher than the fleet average (in 2026) of approximately 2.5 times the limit.

Importantly, implementation of an LEZ would result in an immediate substantial reduction in NO$_X$ emissions (2020–2026) in addition to the sustained emission reductions resulting from a strengthened RDE program. An LEZ implemented in conjunction with an Accelerated RDE+ program would reduce emissions from the average passenger car (operating within the zone) to less than 2 times the Euro 6 diesel limit in 2026 and 1.4 times this limit in 2030. Thus, although the Baseline RDE program would reduce average passenger car NO$_X$ emissions by close to 50% in 2030 (compared to 2015), an LEZ with an Accelerated RDE+ program could achieve this level of NO$_X$ reduction by 2022. Furthermore, the LEZ with Accelerated RDE+ could result in average passenger car emissions that are 75% lower in 2026 and 80% lower in 2030 compared to 2015 levels.
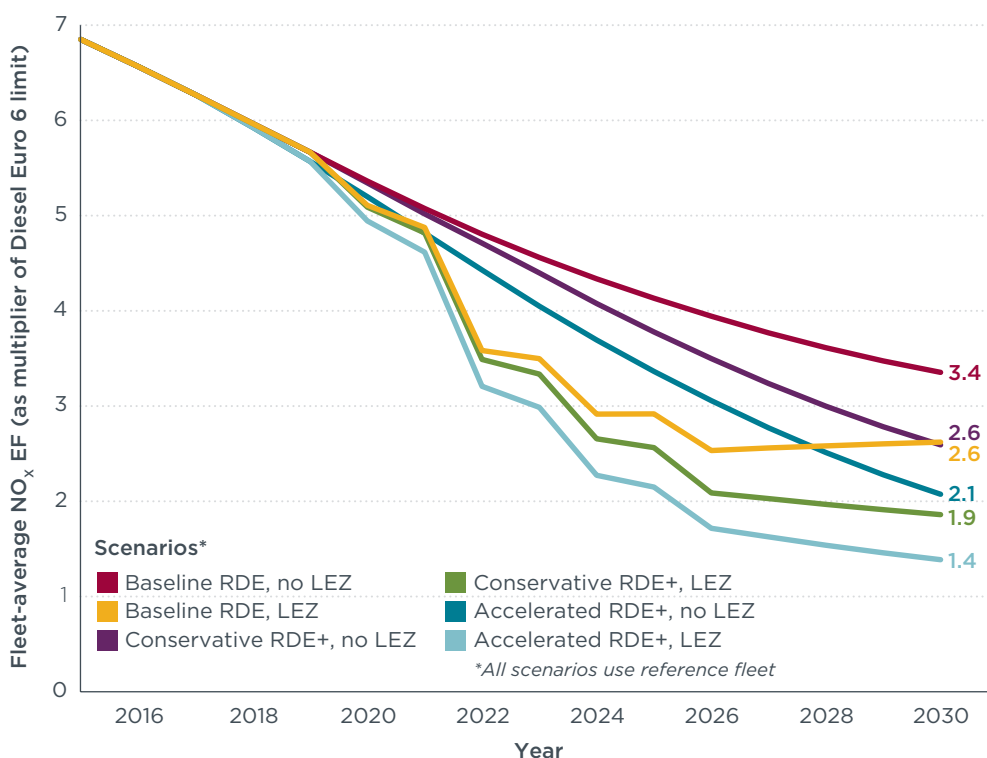

Figure 16. Impact of an LEZ on fleet average passenger car NO$_X$ emission rate, 2015–2030.

4. OUTLOOK

The real-world NO$_X$ noncompliance problem for Euro 5 and Euro 6 diesel passenger cars is more extensive than previously thought. A correspondingly extensive effort from industry, regulators, national type-approval authorities, and other stakeholders will be required to solve it.

4.1 FROM RDE TO RDE+

Allowing real-world emission levels to remain substantially higher than is attainable with currently available technology and enforcement practices (i.e., failing to address the gap between laboratory and on-road NO$_X$ emissions from diesel cars) would undermine the objective of vehicle emissions regulations—namely to improve air quality and public health while setting a level playing field for manufacturers. An RDE regulation that is too lenient will effectively penalize those manufacturers using the best available NO$_X$ control technologies and calibrations. Although the RDE regulation—and also the current proposal for a new emissions type-approval framework in the EU[11]—are steps in the right direction, our analysis also indicates that the ultimate success of these regulations in improving air quality in European cities will depend on the ability of European regulators to make adjustments to the existing RDE framework to achieve improvements in key areas. In particular, our findings highlight the importance of fully developing the third and fourth regulatory packages of RDE as a near-term policy priority.

First, we have shown that the regulated conformity factor (e.g., 2.1 times the Euro 6 limit for the first phase of RDE) and the actual real-world emission multiplier can be two very different numbers. In the case of NO$_X$ from diesel passenger cars, a low nominal conformity factor for the RDE test is not sufficient to lower real-world emissions, because the driving conditions <u>not</u> covered by the RDE test have a relatively high contribution to overall NO$_X$ emissions, despite their minority share of vehicle activity.

Second, we have shown that the distorting effect of defeat devices—legal or otherwise—has a very large impact on both the projected emission factors and in their associated uncertainty. This is shown in Figure 17, where we have plotted the estimated probability density[12] functions for the modeled emission factors resulting from the Monte Carlo simulation (described in Section 2.2.3 and in Annex I). As shown, the benefit of transitioning from RDE+a to RDE+b (from a real-world emission multiplier of 3.3 to one of 2.1, a 37% reduction) is halved (to only 18%) if the assumed effect of lowering the prevalence of defeat devices is removed.[13] This means that real-world emission reductions over the mid-term depend on the effectiveness of improved enforcement in lowering the prevalence of defeat devices and poor real-world NO$_X$ control calibrations. Because the RDE regulation was not devised to detect defeat devices, we view the adoption of in-service conformity testing provisions as an essential addition to achieve the environmental and public health objectives of the RDE regulation. These provisions would ideally include spot checks, incorporate random selection of test vehicles, and institute an appropriate financial penalty regime and effective EU-wide vehicle recall system for noncompliance cases (Défense Terre, 2016).

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11 See http://www.theicct.org/proposed-new-type-approval-framework-eu-policy-update
12 These were estimated using Matlab's *ksdensity* function; see http://www.mathworks.com/help/stats/ksdensity.html
13 This 18% reduction comes after lowering the CF for the RDE test from 2.1 to 1.5, which would be an apparent reduction of 29% if the emission reductions were achieved uniformly under all driving conditions.
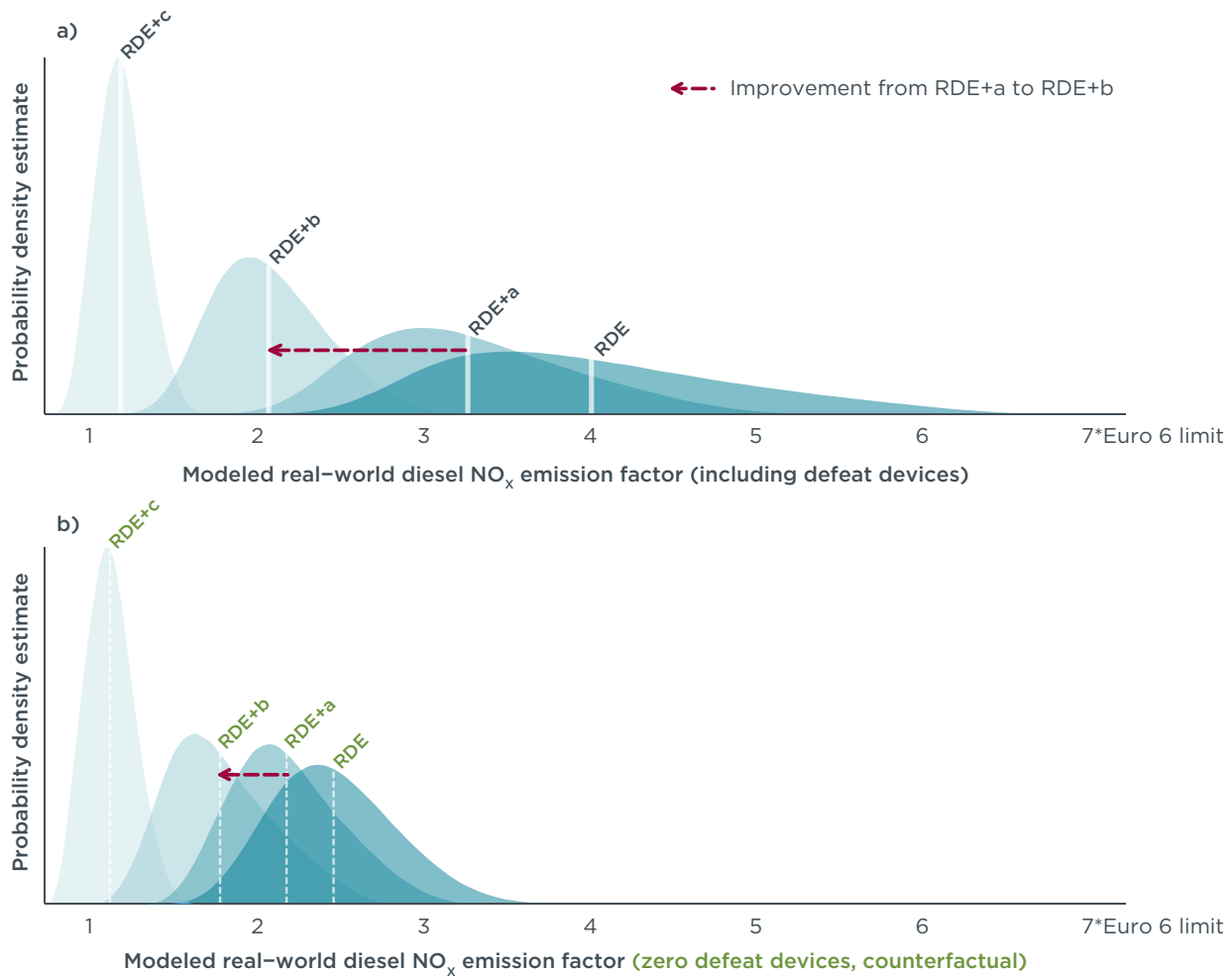
Figure 17. Average emission factors and associated probability density estimates (a) including and (b) excluding the effect of defeat devices and poor NO$_X$ control calibrations.

Third, our analysis can help set realistic expectations of long-term, real-world emissions from diesel passenger cars under various policy and technology scenarios, especially those that are feasible through the adoption and development of RDE. Under the most optimistic scenario that relies on RDE to drive emission reductions (Accelerated RDE+, which includes widespread adoption of best aftertreatment technologies, driven by stringent policies), the long-term NO$_X$ emission factor for newly registered diesel passenger cars reaches a minimum average level of 1.2x the Euro 6 limit by 2022—in line with the results independently modeled in Ntziachristos et al. (2016a)—whereas the Conservative RDE+ scenario only achieves a multiplier of 2.1x the Euro 6 limit by 2023.

In other words, even with a substantial improvement in NO$_X$ technology uptake and enforcement practices, we do not expect the average, comprehensive real-world NO$_X$ emission factor of new diesel cars to drop below the psychological threshold of one (which marks real-world alignment with the regulated emission limit). This finding is relevant not only to regulators in the EU but also in other regions (e.g., India) where diesel accounts for a significant share of the car fleet. Additionally, this finding is an acknowledgment of the significant technological challenge that diesel car manufacturers are facing, as well an opportunity to consider the long-term implications of fuel and technology choice (by manufacturers and consumers alike) for air quality and public health.

Finally, the prospect that real-world NO_X emissions from diesel cars will remain above emission limits highlights the importance of further developing the RDE program to incorporate the improvements evaluated in this paper as well as consider a Euro 7 standard. Factors to consider as part of a Euro 7 standard include: tightening NO_X emission limits for diesel and gasoline cars, setting fuel neutral emission limits, and adopting effective defeat device provisions and penalties (Défense Terre, 2016)—the latter of which also could be implemented independently from a Euro 7 standard. The US Tier 3 program sets a manufacturer fleet average non-methane organic gases (NMOG)+NO_X emission limit of 30 mg/mile (18.6 mg/km) in 2025 as measured on the federal test procedure (FTP) test cycle and 50 mg/mile (31.1 mg/km) as measured on the supplemental federal test procedure (SFTP), the latter of which includes higher speeds, higher acceleration rates, and air conditioning operation. Without controlling for differences in test cycles, these numerical emission limits are approximately 50%–70% below the Euro 6 NO_X emission limit for gasoline cars, which has remained unchanged since the introduction of Euro 5 in 2009. Combined with a strengthened RDE program to improve the real-world performance of individual vehicles, adding manufacturer fleet average emission limits in Europe that are similar in stringency to the US Tier 3 program could encourage manufacturers to implement the most cost-effective NO_X reduction technologies and consider the impact of fuel choice in optimizing emission reductions from their new fleet offerings.

4.2 IMPROVEMENTS WILL TAKE TIME AND EFFORT

Assuming that the share of diesel cars in the fleet remains stable or is progressively reduced, and that new Euro 6 diesel passenger cars have—in absolute terms, if not in relation to the reference legal limits—better NO_X emissions performance than previous technology classes, our modeling results indicate that we are barely past "peak diesel NO_X" in European cities. Therefore, one can reasonably expect that air-quality indicators will improve over time with steady reductions in passenger car NO_X emissions. However, the low turnover rate of the vehicle fleet (which takes decades to renew) and the poor NO_X emissions performance of Euro 4, Euro 5, and early iterations of Euro 6 passenger cars means that the air-quality problems caused by real-world diesel NO_X emissions will linger in the absence of external factors to accelerate emission reductions.

In this paper, we have modeled the evolution of the average passenger car NO_X emission factor using fleet projections for the EU-28. However, the popularity of diesel across different EU member states varies significantly. In general, countries with high dieselization rates and lower-than-average fleet turnover rates (e.g., Spain) will likely face more severe problems than member states with more modern fleets and a lower share of diesel cars (e.g., the Netherlands; see Figure 18).[14] Nevertheless, our projection that diesel cars will continue to account for a disproportionate share of NO_X emissions—even with a potential decline in the market share of new diesel cars—suggests that an improved RDE program would directly benefit all member states with a non-negligible share of diesel car sales. Moreover, the local or regional benefits of such a program could be amplified if LEZs, such as the one we modeled in this paper, were implemented in European cities with pressing air-quality issues.

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14   A more granular analysis (e.g., at the member-state level) is a topic that we aim to investigate further in future work.
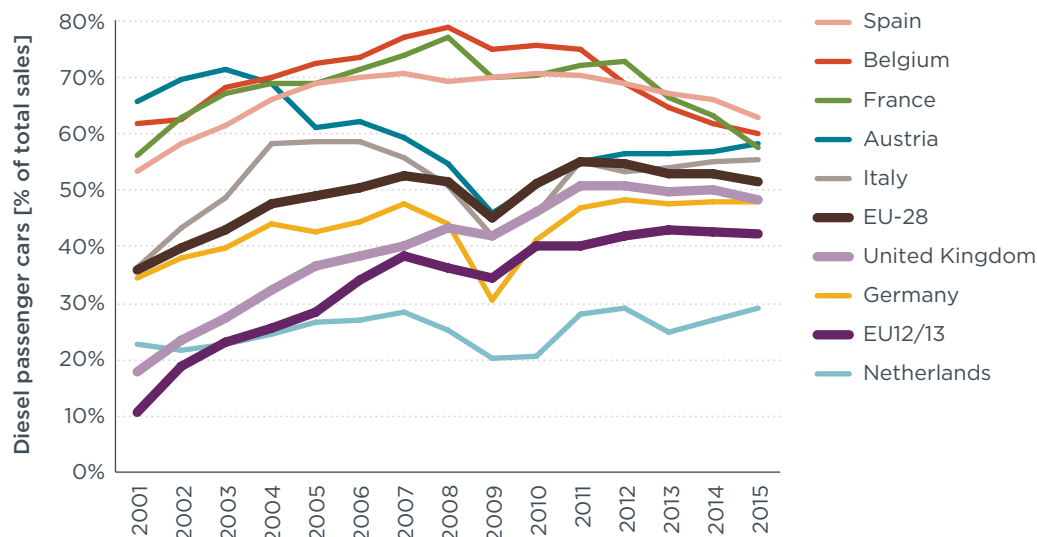
Figure 18. Market share of new diesel passenger cars in select EU member states, 2001–2015 (ICCT, 2016).

4.3 ADDITIONAL CONSIDERATIONS

While tighter regulated conformity factors will play a part in reducing real-world emissions, there are other ways in which the regulation could be made more (or less) robust. Because of the uncertainty surrounding their final implementation, we have not modeled the impact of the so-called "transfer functions": these are proposed experimental functions—currently equivalent to a multiplier of 1 (European Commission, 2016b)—that "correct" the conformity factor for driving situations that deviate from a baseline (representative of normal driving, in most cases related to WLTP testing). Depending on their final implementation, these could be detrimental because they would "flatten" the exponential growth of NO$_X$ emission rates outside the controlled conditions using a mathematical construct instead of actual pollution-control technology. A worst-case assumption would have transfer functions negate the real-world effect of improvements in Key Area 4 (see Section 2.1).

We stress that our estimates for various components of the real-world emission factors (e.g., the "good cold-start" or the "good extended driving") are not proposals for regulated RDE conformity factors, but rather performance targets that we think are achievable with current technology. We also note that, when we generally describe the key areas where further technical work could improve the RDE regulations, we are not prescribing how the improvements should be implemented in the regulation in practice: the details will have to be worked out in the months to come, with the participation of all stakeholders.

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ANNEX I. MATLAB SCRIPT FOR DERIVATION OF REAL-WORLD NO$_X$ EFS (INCLUDING MONTE CARLO SIMULATION)

```
%%Script for the calculation of real-world NOx emission factors for
%diesel passenger cars. ICCT White Paper "Impact of
%improved regulation of real-world NOx emissions from diesel passenger cars
in the EU, 2015-2030"

% %"Random in range" function to be saved as separate m. file [random_in_
range.m; required for
% Monte Carlo Simulation]:

% function [ random_output ] = random_in_range(parameter, symmetrical_range)
% %Random number within parameter plus minus (symmetrical_range)% (used for
% %NOx EF Monte Carlo simulation
% symmetrical_range=symmetrical_range/100;
% a=parameter*(1-symmetrical_range);
% b=parameter*(1+symmetrical_range);
% random_output=(b-a)*rand(1,1)+a;
% end

%%
%PART 1: EF modeling parameters

safety_margin=0.3; % 30% margin of compliance for driving conditions covered
by RDE test

%vkm shares
share.cold_start=0.08; % 8% of total vkm have the 'cold-start'EF
share.extended=0.1; % 10% of total vkm have the 'extended'EF
share.normal=1-share.cold_start-share.extended; % the remaining % of vkm have
the 'normal' EF

%prevalence of defeat devices / poor calibrations
share.defeat.RDE=0.30;
share.defeat.RDEplus_a=0.20;
share.defeat.RDEplus_b=0.05;
share.defeat.RDEplus_c=0.01; % The prevalence of defeat devices/poor
calibrations is progressively lowered from RDE to RDE+c
```

```
    %(All CF values are expressed as multipliers of Euro 6 limit for diesel
NOx [80 mg/km]);
    CF.extended.poor=7.6252;%Median of the averages of worst 20% of CO2
windows for each vehicle (ICCT database, 32 vehicles in total)
    CF.uncontrolled=7.6252;%Same as CF.extended.poor
    CF.extended.good=3.0;%Expert assumption
    CF.cold_start.poor=6.0316; % Median of the averages of the CFs of cold-
start events (average of the first 300 seconds for all trips) for each vehicle
(ICCT database, 32 vehicles in total)
    CF.cold_start.good=2.5;%Expert assumption
        CF.cold_start.good_b=CF.cold_start.good*(1.5/2.1);
        CF.cold_start.good_c=CF.cold_start.good*(1.2/2.1);


    CF.baseline.preRDE=5.6614; % Median of the average EFs of all vehicles
(ICCT database, 32 vehicles in total)
    CF.baseline.RDE=2.1*(1-safety_margin);
    CF.baseline.RDEplus_a=2.1*(1-safety_margin);
    CF.baseline.RDEplus_b=1.5*(1-safety_margin);
    CF.baseline.RDEplus_c=1.2*(1-safety_margin);
%%
%PART 2: EF calculation


EF.preRDE=CF.baseline.preRDE;


%excluding the influence of defeat devices / poor calibrations...
EF.RDE=(share.cold_start*CF.cold_start.poor)+(share.extended*CF.extended.
poor)+(share.normal*CF.baseline.RDE);
EF.RDEplus_a=(share.cold_start*CF.cold_start.good)+(share.extended*CF.
extended.poor)+(share.normal*CF.baseline.RDEplus_a);
EF.RDEplus_b=(share.cold_start*CF.cold_start.good_b)+(share.extended*CF.
extended.poor)+(share.normal*CF.baseline.RDEplus_b);
EF.RDEplus_c=(share.cold_start*CF.cold_start.good_c)+(share.extended*CF.
extended.good)+(share.normal*CF.baseline.RDEplus_c);


%...including the influence of defeat devices / poor calibrations:
EF.RDE_defeat_devices=(1-share.defeat.RDE)*EF.RDE + share.defeat.RDE*CF.
uncontrolled;
EF.RDEplus_a_including_defeat_devices=(1-share.defeat.RDEplus_a)*EF.RDEplus_
a+ share.defeat.RDEplus_a*CF.uncontrolled;
EF.RDEplus_b_including_defeat_devices=(1-share.defeat.RDEplus_b)*EF.RDEplus_
b+share.defeat.RDEplus_b*CF.uncontrolled;
```

```
EF.RDEplus_c_including_defeat_devices=(1-share.defeat.RDEplus_c)*EF.RDEplus_
c+share.defeat.RDEplus_c*CF.uncontrolled;
%%
%PART 3: Monte Carlo simulation

number_of_runs=1000000; %number of runs makes script run time increase
proportionally
percent_variation=50; %random variation that is allowed for the Monte Carlo
simulation parameters

rng('default') %Reset random number generator (to get repeatable results)
for i=1:number_of_runs

%Safety margin
safety_margin_Monte_Carlo(i,1)=random_in_range(safety_margin,percent_
variation);

%vkm shares of driving situations (cold/extended/normal)
share.cold_start_Monte_Carlo(i,1)=random_in_range(share.cold_start,percent_
variation);
share.extended_Monte_Carlo(i,1)=random_in_range(share.extended,percent_
variation);
share.normal_Monte_Carlo(i,1)=1-share.cold_start_Monte_Carlo(i,1)-share.
extended_Monte_Carlo(i,1);

%Share of defeat devices/poor calibrations
share.defeat.RDE_Monte_Carlo(i,1)=random_in_range(share.defeat.RDE,percent_
variation);
share.defeat.RDEplus_a_Monte_Carlo(i,1)=random_in_range(share.defeat.
RDEplus_a,percent_variation);
share.defeat.RDEplus_b_Monte_Carlo(i,1)=random_in_range(share.defeat.
RDEplus_b,percent_variation);
share.defeat.RDEplus_c_Monte_Carlo(i,1)=random_in_range(share.defeat.
RDEplus_c,percent_variation);

CF.uncontrolled_Monte_Carlo(i,1)=random_in_range(CF.uncontrolled,percent_
variation);%Applicable to defeat devices
CF.extended.poor_Monte_Carlo(i,1)=random_in_range(CF.extended.poor,percent_
variation);%Applicable up to RDE+b
CF.extended.good_Monte_Carlo(i,1)=random_in_range(CF.extended.good,percent_
variation);%Applicable to RDE+c
CF.cold_start.poor_Monte_Carlo(i,1)=random_in_range(CF.cold_start.
```

```
poor,percent_variation);%Applicable to RDE
CF.cold_start.good_Monte_Carlo(i,1)=random_in_range(CF.cold_start.
good,percent_variation);%Applicable to RDE+a
    CF.cold_start.good_b_Monte_Carlo(i,1)=random_in_range(CF.cold_start.
good_b,percent_variation);%Applicable to RDE+b
    CF.cold_start.good_c_Monte_Carlo(i,1)=random_in_range(CF.cold_start.
good_c,percent_variation);%Applicable to RDE+c


CF.baseline.RDE_Monte_Carlo(i,1)=2.1*(1-safety_margin_Monte_
Carlo(i,1));%Baseline EFs apply to RDE test conditions
CF.baseline.RDEplus_a_Monte_Carlo(i,1)=2.1*(1-safety_margin_Monte_Carlo(i,1));
CF.baseline.RDEplus_b_Monte_Carlo(i,1)=1.5*(1-safety_margin_Monte_Carlo(i,1));
CF.baseline.RDEplus_c_Monte_Carlo(i,1)=1.2*(1-safety_margin_Monte_Carlo(i,1));


%EFs, by RDE/RDE+ step (excluding the influence of defeat devices / poor
calibrations)
EF.RDE_Monte_Carlo(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_start.
poor_Monte_Carlo(i,1))+(share.extended_Monte_Carlo(i,1)*CF.extended.poor_
Monte_Carlo(i,1))+(share.normal_Monte_Carlo(i,1)*CF.baseline.RDE_Monte_
Carlo(i,1));
EF.RDEplus_a_Monte_Carlo(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_
start.good_Monte_Carlo(i,1))+(share.extended_Monte_Carlo(i,1)*CF.extended.
poor_Monte_Carlo(i,1))+(share.normal_Monte_Carlo(i,1)*CF.baseline.RDEplus_a_
Monte_Carlo(i,1));
EF.RDEplus_b_Monte_Carlo(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_
start.good_b_Monte_Carlo(i,1))+(share.extended_Monte_Carlo(i,1)*CF.extended.
poor_Monte_Carlo(i,1))+(share.normal_Monte_Carlo(i,1)*CF.baseline.RDEplus_b_
Monte_Carlo(i,1));
EF.RDEplus_c_Monte_Carlo(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_
start.good_c_Monte_Carlo(i,1))+(share.extended_Monte_Carlo(i,1)*CF.extended.
good_Monte_Carlo(i,1))+(share.normal_Monte_Carlo(i,1)*CF.baseline.RDEplus_c_
Monte_Carlo(i,1));


%EFs, by RDE/RDE+ step (including the influence of defeat devices / poor
calibrations)
EF.RDE_Monte_Carlo_including_defeat_devices(i,1)=(1-share.defeat.RDE_Monte_
Carlo(i,1))*EF.RDE_Monte_Carlo(i,1) + share.defeat.RDE_Monte_Carlo(i,1)*CF.
uncontrolled_Monte_Carlo(i,1);
EF.RDEplus_a_Monte_Carlo_including_defeat_devices(i,1)=(1-share.defeat.
RDEplus_a_Monte_Carlo(i,1))*EF.RDEplus_a_Monte_Carlo(i,1)+share.defeat.
RDEplus_a_Monte_Carlo(i,1)*CF.uncontrolled_Monte_Carlo(i,1);
EF.RDEplus_b_Monte_Carlo_including_defeat_devices(i,1)=(1-share.defeat.
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RDEplus_b_Monte_Carlo(i,1))*EF.RDEplus_b_Monte_Carlo(i,1)+share.defeat.

RDEplus_b_Monte_Carlo(i,1)*CF.uncontrolled_Monte_Carlo(i,1);

EF.RDEplus_c_Monte_Carlo_including_defeat_devices(i,1)=(1-share.defeat.

RDEplus_c_Monte_Carlo(i,1))*EF.RDEplus_c_Monte_Carlo(i,1)+share.defeat.

RDEplus_c_Monte_Carlo(i,1)*CF.uncontrolled_Monte_Carlo(i,1);


%Contribution to EF (separately for normal [N], cold [C], extended [E] and

defeat device [D] components)

EF.RDE_Monte_Carlo_normal(i,1)=(share.normal_Monte_Carlo(i,1)*CF.baseline.

RDE_Monte_Carlo(i,1))*(1-share.defeat.RDE_Monte_Carlo(i,1));

EF.RDEplus_a_Monte_Carlo_N(i,1)=(share.normal_Monte_Carlo(i,1)*CF.baseline.

RDEplus_a_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_a_Monte_Carlo(i,1));

EF.RDEplus_b_Monte_Carlo_N(i,1)=(share.normal_Monte_Carlo(i,1)*CF.baseline.

RDEplus_b_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_b_Monte_Carlo(i,1));

EF.RDEplus_c_Monte_Carlo_N(i,1)=(share.normal_Monte_Carlo(i,1)*CF.baseline.

RDEplus_c_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_c_Monte_Carlo(i,1));


EF.RDE_Monte_Carlo_C(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_start.

poor_Monte_Carlo(i,1))*(1-share.defeat.RDE_Monte_Carlo(i,1)); %Cold-start

behavior is poor for RDE, improves gradually from RDE+a

EF.RDEplus_a_Monte_Carlo_C(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_

start.good_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_a_Monte_Carlo(i,1));

EF.RDEplus_b_Monte_Carlo_C(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_

start.good_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_b_Monte_Carlo(i,1));

EF.RDEplus_c_Monte_Carlo_C(i,1)=(share.cold_start_Monte_Carlo(i,1)*CF.cold_

start.good_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_c_Monte_Carlo(i,1));


EF.RDE_Monte_Carlo_E(i,1)=(share.extended_Monte_Carlo(i,1)*CF.extended.poor_

Monte_Carlo(i,1))*(1-share.defeat.RDE_Monte_Carlo(i,1));

EF.RDEplus_a_Monte_Carlo_E(i,1)=(share.extended_Monte_Carlo(i,1)*CF.extended.

poor_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_a_Monte_Carlo(i,1));

EF.RDEplus_b_Monte_Carlo_E(i,1)=(share.extended_Monte_Carlo(i,1)*CF.extended.

poor_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_b_Monte_Carlo(i,1));

EF.RDEplus_c_Monte_Carlo_E(i,1)=(share.extended_Monte_Carlo(i,1)*CF.extended.

good_Monte_Carlo(i,1))*(1-share.defeat.RDEplus_c_Monte_Carlo(i,1)); %extended

conditions have good behavior for RDEplus_c


EF.RDE_Monte_Carlo_D(i,1)=share.defeat.RDE_Monte_Carlo(i,1)*CF.uncontrolled_

Monte_Carlo(i,1);

EF.RDEplus_a_Monte_Carlo_D(i,1)=share.defeat.RDEplus_a_Monte_Carlo(i,1)*CF.

uncontrolled_Monte_Carlo(i,1);
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```
EF.RDEplus_b_Monte_Carlo_D(i,1)=share.defeat.RDEplus_b_Monte_Carlo(i,1)*CF.
uncontrolled_Monte_Carlo(i,1);
EF.RDEplus_c_Monte_Carlo_D(i,1)=share.defeat.RDEplus_c_Monte_Carlo(i,1)*CF.
uncontrolled_Monte_Carlo(i,1);


end


clearvars i CF number_of_runs percent_variation
```

LIST OF ACRONYMS

CF	conformity factor
DPF	diesel particulate filter
EC-JRC	European Commission (Directorate-General Joint Research Centre)
EF	emission factor
EU	European Union
EU-28	28 member states of the European Union
FTP	federal test procedure (US emissions test cycle)
ICCT	The International Council on Clean Transportation
LEZ	low-emission zone
LNT	lean NO_x trap (NO_x emissions-control technology)
NEDC	New European Driving Cycle
NMOG	non-methane organic gases
NO_x	nitrogen oxide
PM	particulate matter
PEMS	portable emission measurement system
RDE	real-driving emissions
RDE-LDV	Real-Driving Emissions–Light-Duty Vehicles working group
SCR	selective catalytic reduction (NO_x emissions-control technology)
SFTP	supplemental federal test procedure (US emissions test cycle)
vkm	vehicle-kilometers
WLTP	Worldwide Harmonized Light Vehicles Test Procedure