WHITE PAPER

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REAL-WORLD EXHAUST EMISSIONS FROM MODERN DIESEL CARS

A META-ANALYSIS OF PEMS EMISSIONS DATA FROM EU (EURO 6) AND US (TIER 2 BIN 5/ULEV II) DIESEL PASSENGER CARS.

PART 1: AGGREGATED RESULTS

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ABOUT THIS DOCUMENT

Our “Real-World Exhaust Emissions from Modern Diesel Cars” report has been divided into two parts. The present document **(Part 1: Aggregated results),** which can be read as a standalone, introduces the study and presents the aggregated results of our assessment (i.e., at vehicle or vehicle class level). It is intended to appeal to a broad public that includes vehicle emission scientists and policymakers in the field of vehicle emissions.

The second part of this report (**Part 2: Detailed results** [Franco, Posada Sánchez, German, & Mock, 2014]) is aimed at vehicle emission scientists who wish to take a closer look at the on-road emission performance of the vehicles under study. It supplements the results presented in Part 1 by presenting the measured data with a higher level of granularity, using a series of standard data tables and graphical representations of the results that are repeated for each one of the PEMS trips covered in the meta-analysis. This second part also includes explanations on how to read and interpret the detailed charts.

EXECUTIVE SUMMARY

This report presents the general assessment of the on-road emission behavior of several different modern diesel passenger cars tested in Europe and in the US using portable emissions measurement systems (PEMS). The level of detail of the analysis and the large number of vehicles (15) and trips covered in the assessment (97, for a total of more than 140 hours and 6,400 kilometers driven) make this the most comprehensive report on the on-road behavior of the latest generation of diesel passenger cars published to date.

The data for US vehicles come from a measurement campaign sponsored by the ICCT (and whose results were previously reported in Thompson, Carder, Besch, Thiruvengadam, & Kappana, 2014). The European vehicle data were generously provided by third parties, all but one of which are stakeholders in the European Commission's working group in charge of amending the Euro 6 regulations to include real-driving emissions testing as a part of the type-approval process of light-duty vehicles in the EU, the Real Driving Emissions of Light-Duty Vehicles (RDE-LDV) group.

The raw experimental results were processed using a consistent data preprocessing, analysis, and reporting framework presented for the first time in this report. This framework allows for a clear visualization of the general behavior of individual vehicles over single trips or collections of trips, as well as a detailed assessment of the operating conditions that lead to high-emission events.

The main findings of the assessment are consistent with the existing body of evidence indicating that modern diesel passenger cars have low on-road emissions of carbon monoxide (CO) and total hydrocarbons (THC), but an unsatisfactory real-world emission profile of nitrogen oxides (NO_x). Particulate matter (PM) and particle number (PN) measurements were absent from most of the datasets and are therefore excluded from this report.

This report presents strong evidence of a real-world NO_x compliance issue for recent-technology diesel passenger cars, both for the EU and US test vehicles. The high temporal and spatial resolution of PEMS datasets was used to link the elevated NO_x mass emission rates to the driving conditions that cause them. It was found that a sizable share of NO_x emissions over individual test trips (typically lasting about one hour) were concentrated over a number of discrete emission spikes spanning a few seconds. These emission events, which varied in frequency from vehicle to vehicle, could not be attributed to "extreme" or "untypical" driving in most cases. Instead, they were due to transient increases in engine load that constitute real-world driving (e.g., uphill driving, acceleration on a ramp, or positive accelerations from a standstill), or to regeneration events that are part of the normal operation of diesel exhaust aftertreatment systems.

The average, on-road emission levels of NO_x were estimated at 7 times the certified emission limit for Euro 6 vehicles. There were, however, some remarkable differences among the performance of all the vehicles tested, with a few vehicles performing substantially better than the others (Figure 1). *This supports the notion that the technologies for "real-world clean" diesels (i.e., vehicles whose average emission levels lie below Euro 6 emission limits under real-world driving) already exist*. Policies are needed to ensure that manufacturers will use these technologies and calibrate them to effectively control emissions over the large majority of in-use operating conditions, not just those covered by the test cycle.

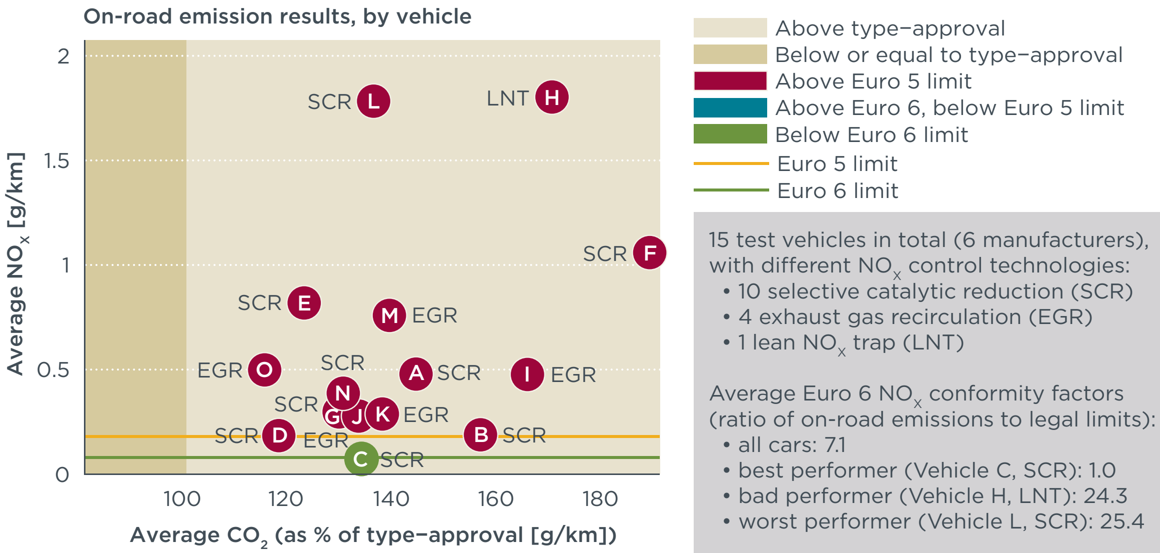

Figure 1: Overview of on-road NO_x and CO_2 emission results for all vehicles under test

Unless the appropriate technical measures are adopted, the high on-road emissions of NO_x from the new diesel technology classes of passenger cars could have serious adverse health effects on the exposed population. Regulatory action is urgently required in Europe, where all new diesel passenger cars sold from September 2014 belong to the Euro 6 class and the regional share of diesel vehicles in the passenger car fleet is higher than anywhere else in the world. In this sense, the European RDE-LDV initiative (Weiss, Bonnel, Hummel, & Steininger, 2013) requiring the inclusion of on-road testing with PEMS as part of the passenger car type-approval process in the EU is a step in the right direction. However, the existence of the real-world diesel NO_x issue must be acknowledged by regulators in its full extent and subsequently addressed in collaboration with vehicle manufacturers and other stakeholders.

Keywords: Diesel cars, real-world emissions, PEMS, air quality, NO_x, fuel consumption, Euro 6, Tier 2 Bin 5, NEDC, FTP, RDE-LDV, type-approval

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ABBREVIATIONS

CF	Conformity factor
CO	Carbon monoxide
CO_2	Carbon dioxide
DPF	Diesel particulate filter
EC	European Commission
EC-JRC	European Commission—Joint Research Centre
EF	Emission factor
EGR	Exhaust gas recirculation
EU	European Union
FTP	Federal test procedure
g/km	Grams per kilometer
g/min	Grams per minute
GPS	Global positioning system
HDV	Heavy-duty vehicle
HVAC	Heating, ventilation and air conditioning
Hz	Hertz
ID	Identifier
kg	kilogram
km	kilometer
LNT	Lean NO_x trap
mg/km	milligrams per kilometer
mg/mi	milligrams per mile
NEDC	New European driving cycle
NH_3	Ammonia
NO_x	Nitrogen oxides
NTE	Not to exceed
OBD	On-board diagnostics
PEMS	Portable emissions measurement system
PN	Particle number
RDE-LDV	Real driving emissions from light-duty vehicles
SCR	Selective catalytic reduction
THC	Total hydrocarbons
ULEV	Ultra-low-emission vehicle
US	United States of America

1 INTRODUCTION

Diesel passenger cars have become very popular in Europe over the past two decades. Many European customers have favored them in spite of their higher purchase price because diesel fuel has been historically cheaper than gasoline in Europe. Diesel cars are typically more fuel-efficient than their gasoline counterparts, and they are also broadly perceived as being more durable and reliable. Over the past years, the improved availability and quality of diesel fuel has also sparked interest in diesel cars in the US.

Strong demand from the domestic market has turned European manufacturers into global leaders in diesel passenger car technology. The dieselization of the European car fleet has made a positive contribution to meeting regional CO_2 targets (Fontaras & Samaras, 2007), and the newest Euro 6 diesel cars meet stringent emission limits for regulated pollutants (CO, NO_x, particle mass and number, and total hydrocarbons). However, as explained in Section 2 of this report, these emission limits are evaluated with a standard test performed under predefined conditions in a chassis dynamometer laboratory (Franco et al., 2013). There is substantial evidence that the actual, on-road emissions may not be sufficiently controlled under certain operating conditions that are not covered by the laboratory test. As a result, and contrary to expectations, real-world emission levels of NO_x have been reported to increase with the introduction of the Euro 5 and Euro 6 technology classes (Chen & Borken-Kleefeld, 2014; Fontaras, Franco, Dilara, Martini, & Manfredi, 2013; Ligterink, Kadijk, van Mensch, Hausberger, & Rexeis, 2013; Weiss et al., 2011). In some cases, the measured NO_x emission rates for the more demanding driving conditions not covered by the type-approval cycle were several times higher than the relevant emission limits.

The previous studies were limited to a handful of vehicles, and they provided inconclusive evidence of a widespread on-road compliance problem. However, the results prompted research efforts by the ICCT and other research partners to gather emissions data from additional vehicles. This report compiles the on-road emissions datasets gathered from different measurement campaigns that made use of on-board exhaust gas analyzers (i.e., PEMS) and analyzes the real-world emission profile of current technology diesel passenger cars sold in the EU and US markets.

The measurement campaigns—briefly described in Section 3—were carried out in the EU and US by the ICCT and other research partners who generously shared their data to support our meta-study. More than 140 hours worth of second-by-second data were collected from several sources covering a combined total of more than 6,400 km driven for 15 test vehicles. This makes our meta-study the most comprehensive of its kind published to date. The results presented in this report provide a sound experimental basis for the statistical characterization of the emission profile of the latest diesel passenger cars. In our view, they are also robust enough to justify more stringent regulations to control emissions from these vehicles.

Due to the heterogeneous origin of the data, and in order to facilitate the comparisons across different measurement campaigns, vehicles, and testing conditions, we developed a consistent framework for the analysis and reporting of the results. This allowed us to characterize the general behavior of the vehicles and to identify the operating conditions that lead to high emissions. The most significant product of this framework (described in Section 4) is a series of standard PEMS charts and summary tables that can be produced for individual PEMS trips or collections of trips, allowing us to compare the on-road emissions of regulated pollutants of the test cars to the relevant legal emission limits and corresponding type-approval results, and to visualize the operating conditions that lead to elevated instantaneous emissions.

The high-level results of our analysis are provided in Section 5 of this document, along with discussion of current efforts to include PEMS testing as part of the type-approval process for Euro 6 passenger cars in Europe (Weiss et al., 2013).

The second part of this report, featuring the complete collection of standard PEMS charts for all the trips covered in the report, can be downloaded from ICCT's website.

2 BACKGROUND

In this section, we briefly introduce the "real-world" emissions problem affecting current passenger cars—i.e., the discrepancy between certified emission levels from laboratory testing and actual, on-road emissions under realistic driving conditions—with special attention to NO_x emissions from diesel passenger cars. We also give an overview of the regulatory landscape for diesel passenger cars in the EU and US, of the main NO_x aftertreatment technologies used in modern diesel passenger cars, and of the on-road emissions measurement technique used in the experimental campaigns covered in this report (PEMS).

2.1 THE REAL-WORLD EMISSIONS PROBLEM

Standards are in place to control the emissions of passenger cars worldwide. Most regions have established enforceable emission limits for CO_2 (which is directly linked to fuel efficiency) and for other pollutants with adverse health effects, typically CO, NO_x, PM, and THC. These emission limits are linked to a standardized chassis dynamometer test cycle, which is a predetermined time-speed profile that the vehicle under test has to follow in an emissions laboratory while its exhaust emissions are measured.

Standard emissions certification tests are carried out as part of regulated vehicle type-approval processes. Ideally, the driving cycle and other aspects of the test procedure will have been laid out in such a way that they provide a realistic approximation of the actual conditions vehicles encounter on the road. However, this is not always possible because the emission tests must have narrow boundary conditions to ensure that results from different vehicles can be directly compared, and that all vehicles sold in a given market are held to the same standards.

This situation has led to vehicle emissions being certified through laboratory procedures that cannot capture the whole range of operating conditions vehicles encounter during real use. At the same time, the increased levels of stringency (e.g., NO_x emission limits for diesel passenger cars on the basis of the NEDC driving cycle were reduced by 68% from Euro 4 to Euro 6) and the lack of updates to the type-approval procedures in some jurisdictions have encouraged engineering strategies that ensure good fuel efficiency and compliance with the relevant emission limits—as long as the vehicles are operated within the narrow boundary conditions of the standardized test, but not necessarily during normal use.

2.2 ON-BOARD EMISSION MEASUREMENTS

Vehicle emissions are typically tested in laboratories equipped with a chassis dynamometer. During chassis dynamometer testing, the vehicle under test remains stationary on a set of rollers that simulate driving resistance, and its emissions are collected and analyzed as it is driven according to a standard time/velocity profile known as the driving cycle. Measuring emissions under controlled conditions in a laboratory increases the repeatability and the comparability of results, which makes this an excellent approach for vehicle type-approval tests. However, it is also an artificial way of measuring emissions, and its results may differ from the actual on-road emissions[1] because it eliminates several factors that influence emissions (e.g., road gradient, hard accelerations, use of air conditioning, and traffic or weather conditions).

1 ICCT has investigated the discrepancy between laboratory and on-road fuel consumption figures for passenger cars in Europe and the US (Mock et al., 2013).

Vehicle emissions of individual vehicles can also be measured with so-called real-world techniques such as remote sensing (Bishop, Starkey, Ihlenfeldt, Williams, & Stedman, 1989) and PEMS, (Vojtíšek-Lom & Cobb, 1997). The data reported in this document were collected using PEMS, which are complete sets of emission measurement instruments that can be carried on board the vehicle to record instantaneous emission rates of selected pollutants with good levels of accuracy. A PEMS unit usually comprises a set of gas analyzers with sample lines (some of which may be heated) directly connected to the tailpipe, plus an engine diagnostics scanner designed to connect with the on-board diagnostics (OBD) link of the vehicle (Figure 2).

Figure 2: Passenger car instrumented with PEMS[2]

PEMS is a relatively new technology that has experienced remarkable development over the past two decades, with improved gas measurement principles and significant reductions in size, weight, and overall complexity. PEMS are relatively simple and inexpensive to purchase and maintain in comparison to a full dynamometer test cell, and they have thus become a popular tool for scientific studies. In recent years, they have also been applied for regulatory purposes. US authorities have introduced additional emissions requirements based upon PEMS testing and the "not to exceed" (NTE) concept, whereby emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve (US EPA, 2005). In Europe, PEMS are being used to verify the in-service conformity of Euro V and Euro VI heavy-duty vehicles with the applicable emissions standards (EC, 2011, 2012), and the EC is working with stakeholders in the Real Driving Emissions from Light-Duty Vehicles group (RDE-LDV) to include PEMS testing as part of the type-approval process of Euro 6 passenger cars (Weiss et al., 2013).

PEMS typically measure instantaneous raw exhaust emissions of CO_2, CO, NO_X, and THC. Portable particle mass analyzers have recently become commercially available after

2 Photo credit: European Commission—Joint Research Centre (EC-JRC).

extensive testing (Mamakos et al., 2011), and portable particle number (PN) analyzers are now reaching the market in anticipation of their application to RDE measurements. Still, the range of pollutants that can be measured with PEMS is limited in comparison to laboratory measurements.

Other limitations of PEMS include the added mass (of approximately 30 to 70 kg, and up to 150 kg if several pollutants are simultaneously measured) that may bias the measurement, and the reduced repeatability due to real-world sources of variability (e.g., traffic or weather conditions).

2.3 TECHNOLOGIES FOR EURO 6 DIESEL COMPLIANCE

The Euro 6 standard entered into force on September 1, 2014, for the type approval of new types of cars in the EU. From January 2015, it will apply to the registration and sale of *all new cars*. One of the biggest technological challenges of the transition from Euro 5 to Euro 6 for diesel passenger cars is the achievement of the required 66% reduction of NO_x emissions over the New European Driving Cycle (NEDC; see Table 1).

Table 1: Applicable Euro 5 and Euro 6 emission limits for diesel passenger cars

Diesel emission limits [mg/km over NEDC cycle]					
Pollutant	**CO**	**NO_x**	**PM**	**THC+NO_x**	**PN [#/km over NEDC cycle]**
Euro 5a	500	180	5.0	230	–
Euro 5b/b+	500	180	4.5	230	6.0E11
Euro 6b/6c	500	80	4.5	170	6.0E11

Aftertreatment NO_x control for Euro 6 light-duty vehicles is based primarily on two technologies: lean NO_x traps (LNTs) and selective catalytic reduction (SCR). These technologies can be applied in combination with exhaust gas recirculation (EGR, which has been applied since the adoption of Euro 2 in the 1990s) or with in-cylinder control strategies (e.g., fuel injection delay and other combustion improvements that reduce the need for aftertreatment systems).

LNTs, currently used in light-duty diesel vehicles in the US and Europe, have shown good durability and NO_x reduction performance during chassis dynamometer testing, in which they match the performance levels of SCR systems (Johnson, 2009). The advantages of an LNT compared with an SCR system are that it is generally more economical for engines with displacements of less than 2.0 liters (Posada, Bandivadekar, & German, 2013). LNTs are also likely more acceptable to customers because they do not require periodic refilling with urea, although LNT operation has a small impact on fuel consumption (Johnson, 2009). The advantages of SCR are that it is generally more economical for engine above 2.0 liters and it can provide better fuel economy and CO_2 emissions through engine tuning for low PM and high engine-out NO_x emissions. The specific technology selected by manufacturers (SCR or LNT) depends not only on emission standards, but also on fuel economy strategies that are covered under CO_2 emission standards. Manufacturers will likely choose the NO_x aftertreatment technology based on a combination of factors that include cost, technical complexity, reliability, fuel economy, and consumer acceptance.

In the sections that follow, the technologies used to achieve Euro 6 diesel compliance (i.e., below or equal to 80 mg/km over NEDC) are briefly discussed. These include SCR and LNT, as well as EGR and in-cylinder control strategies.

2.3.1 In-cylinder control

Current combustion engine design technology makes it possible to achieve Euro 6 levels for NO_x with in-cylinder control strategies, i.e., adjusting the combustion process to keep engine-out emissions at a sufficiently low level. Low NO_x emissions can be accomplished through a combination of aggressive EGR (see Section 2.3.2), compression ratio reduction, use of two-stage turbocharging, variable valve lift, combustion chamber reshaping, and a reduction of fuel injection pressure (Terazawa, Nakai, Kataoka, & Sakono, 2011).

A shortcoming of relying solely on in-cylinder control strategies to control NO_x is related to high-load operation. Engine-out NO_x emissions are known to rise sharply with increased engine loads, while some type-approval test cycles, such as the NEDC, do not include high-load events. This means that a vehicle without specific NO_x aftertreatment could be type-approved to a very stringent NO_x emission standard and yet have an unsatisfactory emission behavior during higher-load in-use operation (e.g., during acceleration periods or higher speeds).

2.3.2 Exhaust gas recirculation (EGR)

EGR systems work by routing a portion (controlled by the EGR valve) of engine-out exhaust gas back to the intake manifold. Since exhaust gas has a lower oxygen content than intake air, the effect of EGR is to lower the oxygen content in the cylinder, which leads to a cooler combustion process and a lower level of NO_x formation. Some EGR systems incorporate a heat exchanger to further cool the exhaust gas before recirculation.

EGR is a proven technology that became widespread after the introduction of Euro 4 and Euro 5 regulations in Europe, and it is used for both gasoline and diesel engines (with the latter being able to apply EGR at rates above 60% under some operating conditions).

A disadvantage of EGR is that the maximum exhaust recirculation rate that can be applied while maintaining stable combustion decreases with engine load (Zheng, Reader, & Hawley, 2004). Therefore, it primarily reduces NO_x formation during low load operation, and not during real-world high-load events.

2.3.3 Selective catalytic reduction (SCR)

SCR is an exhaust aftertreatment technology that uses a catalyst to chemically break down NO_x. This requires the injection of variable amounts of an external reducing agent, which is stored in a separate tank that needs to be periodically refilled. Most SCR systems use an aqueous urea solution (sometimes referred to as diesel exhaust fluid) for this purpose. Urea vaporizes in the exhaust to yield CO_2 and ammonia (NH_3). NO_x emissions in the exhaust gas react with the NH_3 in the catalyst to yield gaseous nitrogen (N_2) and water.

SCR technology has been deployed in HDVs since the adoption of Euro IV. Although there have been substantial advances in SCR technology for light-duty applications, SCR systems in passenger cars face similar challenges as in HDV applications. These challenges are related to low-temperature operation during cold start and urban driving conditions, as well as precisely matching urea injection with NO_x emissions (Johnson, 2014).

The effectiveness of an SCR system in reducing NO_x emissions is dependent on a host of design parameters, including catalyst material, catalyst volume, urea dosing/control strategy, and physical system layout. It is also temperature-dependent: Below some threshold for exhaust temperature, the injected urea cannot be converted to NH_3. At low exhaust temperatures, catalyst activity also falls sharply.

Urban driving is typically characterized by low-speed, stop-and-go conditions, which put a relatively low average load on a vehicle's engine. Exhaust temperature generally varies with engine load, and diesel exhaust temperatures are lower than those of gasoline exhaust. At idle, diesel exhaust temperature can be as low as 100°C, increasing to more than 500°C as load approaches its peak. Various aspects of system design affect the operating temperature thresholds of SCR, but the primary factor is the use of vanadium-based catalysts in virtually all European SCR systems. While vanadium-based catalysts offer some advantages (low cost, good sulfur tolerance), they have relatively poor low-temperature performance relative to other catalyst options. The low-temperature activity of vanadium catalysts can be improved by optimizing the ratio of NO to NO_2 in the exhaust using an oxidation catalyst ahead of the SCR catalyst. Alternatively, copper-zeolite catalysts with greater low-temperature activity can be used, but these are more expensive and more sensitive to the presence of sulfur in the fuel.

The performance of SCR systems can be improved with thermal management to increase exhaust temperatures (Bergmann, 2013). Start-stop systems are also effective at keeping the SCR system warm by avoiding the cooler exhaust temperature of idling conditions. Low-temperature catalyst activity can be improved by increasing catalyst volume, regardless of catalyst material, or by optimizing ammonia storage in the catalyst via different dosing strategies. The latter strategy, however, may increase tailpipe NH_3 emissions ("ammonia slip") in the absence of an effective ammonia slip catalyst downstream of the SCR catalyst (Lowell & Kamakaté, 2012). Further technical details on current SCR systems for diesel passenger cars can be found in Braun et al., 2014.

2.3.4 Lean NO_x traps (LNTs)

Lean NO_x traps combine oxidation and reduction catalysts with an NO_x adsorber that chemically binds and stores NO_x under lean-burn conditions (i.e., when engines operate with an excess of air with respect to the stoichiometric air to fuel ratio). Some applications use the oxidation catalyst to convert NO to NO_2 and store it as nitrate on the alkaline earth oxide washcoat. When the NO_x trap is saturated, it needs to be regenerated by switching engine operation to stoichiometric or fuel-rich (i.e., with an excess of fuel) for a few seconds. This causes the stored NO_x to be desorbed and subsequently reduced to N_2 and O_2 in the reduction catalyst (e.g., a conventional three-way catalyst) downstream of the adsorber.

Unlike SCR systems, LNTs do not require an external reducing agent, and they are also generally lighter and more compact than SCRs. However, the periodical regeneration of the trap imposes a small fuel penalty. NO_x adsorbers also adsorb sulfur oxides and therefore require ultra-low sulfur content (below 15 ppm) in the diesel fuel. Also, since sulfur oxides are more difficult to desorb than NO_x, LNTs need to run periodical desulfation regeneration cycles to remove them.

Two of the most challenging aspects of LNT integration in a vehicle are establishing engine operating conditions for adequate NO_x reduction while minimizing fuel consumption, and dealing with cold start conditions. Typical fuel penalties are in the order of

2–4% (Majewski, 2007). Reducing light-off temperatures during cold starts can be accomplished through thermal management, or with delayed injection during start-up periods. Another problem with LNTs is that the NO_x storage capacity of the catalyst is fixed. This means that, as engine load increases, the frequency of trap regeneration events also needs to increase, and this carries additional fuel penalties.

3 DATA SOURCES

The data presented in this report cover a total of 15 vehicles. The vehicles were anonymized[3] and designated with letter codes (A to O; see Table 2). Individual PEMS trips were assigned a unique ID using the letter code of the vehicle followed by consecutive numbering. This naming convention is used for Part 2 of this report.

The emissions data were collected during different measurement campaigns carried out by different institutions.

» One of these campaigns—which was commissioned to West Virginia University (WVU) by the ICCT—was carried out in the US with US-spec vehicles certified to the US Tier 2 Bin 5/California LEV II standard. The technical details of this campaign (which covered Vehicles B, F and H in Table 2) have been reported in detail elsewhere (Thompson et al., 2014).

» The PEMS trip data for Vehicles C, J, K, L, M and N (all Euro 6 vehicles) were purchased by the ICCT from Emissions Analytics, a UK-based emissions consultancy with vast experience in PEMS testing. Only one trip was available for each vehicle, all following the same route.

» The rest of the datasets (covering Vehicles A, D, E, G, I and O) were gathered from stakeholders of the RDE group that generously contributed to this work. All these tests were carried out on Euro 6 passenger cars. The data contributors did not include vehicle manufacturers or environmental NGOs.

3 Some vehicles were anonymized to comply with requests from third-party data contributors. Ultimately, all the vehicles in the meta-study were anonymized to avoid an uneven treatment of vehicle manufacturers. This decision, which is contrary to the ICCT's usual practice, also affected the vehicles analyzed in Thompson et al., 2014.

Table 2 Overview of vehicles included in the analysis

ID	Body type	NO_x control	Emission standard	Total trips	Data source	Make	Starting mileage [km]
A	SUV	SCR+LNT	Euro 6b	6	Anonymous 1	M1	22,900
B	SUV	SCR	Tier 2 Bin 5/ ULEV II	8	WVU/ICCT	M1	24,200
C	Sedan	SCR	Euro 6	1	Emissions Analytics	M1	4,900
D	Station wagon	SCR	Euro 6	25	Anonymous 2	M2	22,000
E	Sedan	SCR	Euro 6	9	Anonymous 3	M2	N/A
F	Sedan	SCR	Tier 2 Bin 5/ ULEV II	15	WVU/ICCT	M2	24,500
G	Sedan	SCR	Euro 6b	6	Anonymous 1	M2	13,500
H	Sedan	LNT	Tier 2 Bin 5/ ULEV II	13	WVU/ICCT	M2	7,600
I	Sedan	EGR + in-cylinder	Euro 6	4	Anonymous 2	M3	7,600
J	Station wagon	EGR + in-cylinder	Euro 6	1	Emissions Analytics	M3	200
K	Sedan	EGR + in-cylinder	Euro 6	1	Emissions Analytics	M3	1,600
L	Luxury sedan	SCR	Euro 6	1	Emissions Analytics	M4	1,400
M	Minivan	SCR	Euro 6	1	Emissions Analytics	M5	3,500
N	Sedan	SCR	Euro 6	1	Emissions Analytics	M6	1,500
O	Hatchback	Dual EGR	Euro 6b	5	Anonymous 1	M6	11,000

3.1 ABOUT THE TEST VEHICLES

An ideal selection of test vehicles would have covered as many manufacturers, models, and aftertreatment technologies as possible. It should have also been done independently from manufacturers (e.g., by renting the vehicles to perform the tests). However, with the exception of the US testing (where these principles were followed), the selection of the test vehicles was performed without the intervention of the ICCT. This circumstance, coupled with the low availability of Euro 6 vehicles in the market, has led to an uneven coverage of makes and models in the test vehicle lineup. In total, 15 vehicles from six manufacturers were tested. Most of the trips were by vehicles equipped with SCR technology for the aftertreatment of NO_x emissions. Four vehicles (three of them from the same manufacturer) had no specific NO_x aftertreatment system, and only one of our test vehicles (Vehicle H) was equipped with a single LNT. Below are a few further remarks on the final composition of the test vehicle selection:

» Vehicle D was a pre-series vehicles furnished by the corresponding manufacturer. This may have had implications in the emission levels observed for this vehicle (see discussion in Section 5.2).

- Vehicles D, E and G are the same make and model, as is Vehicle F (but the latter is the US-spec vehicle instead of the EU model).
- Vehicles A and B are also the same make and model; A is the EU-spec vehicle and B is the vehicle for the US market. Their NO_x aftertreatment systems differ slightly. The EU vehicle incorporates an LNT in combination with an SCR system, while the US vehicle used only an SCR system.
- Vehicles I and J are the same make, model, and engine type; Vehicle K is the same make and model as Vehicles I and J, but it had a higher-powered engine (and a sweet stereo system).
- The ICCT purchased the data for Vehicles C, J, K, L, M, and N. These measurements were initially performed by Emissions Analytics independently from the ICCT and for a purpose unrelated to this report.

3.2 ABOUT TEST ROUTE COMPOSITIONS AND DRIVING STYLES

The PEMS trips analyzed in this report come from several different testing campaigns. The cars were therefore driven on different routes, and the relative shares of urban/rural/motorway driving, road gradients, and driving styles all differed as well. In some cases, the vehicles were driven repeatedly over the same route or collection of routes. For some vehicles, only a single PEMS trip is available for analysis.

This heterogeneity has some disadvantages, because it makes the comparisons of trip averages less meaningful (as they may be distorted by the aforementioned sources of on-road variability). However, a wide variability of driving conditions also has the advantage of allowing us to identify the factors that lead to high (and low) levels of on-road emissions, provided that the data are properly analyzed. The emissions data analysis techniques that we applied in this work (described in Section 4) allowed us to report the measured emission levels not just as trip averages, but also as a function of several driving situations pertinent to the route composition and the driving style. Furthermore, a detailed characterization of the individual PEMS trips can be found in Part 2 of this report.

4 DATA ANALYSIS

The analysis was performed according to a consistent framework for data preprocessing, analysis and reporting that is presented for the first time in this report. This framework allows for a clear visualization of the general behavior of individual vehicles over single trips or collection of trips, as well as a detailed assessment of the operating conditions that lead to high-emission events. It also makes it possible (with the limitations inherent to the differences in instrumentation, route selection, and driving conditions) to compare emission levels from different datasets.

The data preprocessing, analysis, and reporting was done in a semiautomatic manner through a set of Matlab scripts developed by the ICCT, which were also used to produce the charts in this report. In the following sections, we will describe the most relevant aspects of this methodological framework for the treatment of PEMS data. This background information should help with the interpretation of the results provided in Section 5, as well as the collection of PEMS charts presented in Part 2 of this report.

4.1 KEY PRINCIPLES

The key principles of the analysis are as follows:

- *No data exclusions*. All of the measured emissions data available for each trip were included in the analysis, and they are initially reported without exclusions. This means, for example, that cold starts or DPF regeneration events were not treated separately. This helps ensure that the real-world emission levels reported are not influenced by the arbitrary removal of certain sections where the driving conditions are deemed "untypical." For each trip, the emissions were also evaluated after the application of two different sets of dynamic boundary conditions that exclude the more demanding driving conditions[4] (called "Undemanding driving 1" and "Undemanding driving 2"; see section 4.2.2).
- *Emissions in context*. Whenever appropriate, the measured emission levels are compared with the relevant Euro 5 and Euro 6 emission limits,[5] or with the type-approval CO_2 values of the vehicles under test. The operating conditions of the vehicle during the trip (velocity, acceleration, road gradient, and exhaust temperature) are also linked to differences in the emission levels. For the purpose of this report, we will refer to this aspect of the analysis as "on-road compliance," even though strictly speaking there is no legal obligation for vehicles to comply with the emission limits for regulated pollutants once they have passed the type-approval test.[6]
- *Multiple detail levels*. PEMS charts exist for different levels of data aggregations: from vehicle and trip averages to instantaneous, second-by-second emissions. When appropriate, emission signals are windowed (see Section 4.3) to optimize the amount of information extracted from the PEMS datasets.
- *Consistent visualization of results*. A consistent color scheme is used throughout the different charts and tables used to present the results in both parts of this report.

4 The emission levels resulting from this analysis are only representative of the mild driving conditions that they cover, and they should not be construed as the ICCT's definition of what constitutes normal driving.

5 The legal Euro 5 and Euro 6 limits are provided only for reference, as they apply solely to the NEDC chassis dynamometer driving cycle.

6 The emission levels of the three Tier 2 Bin 5/ULEV II vehicles are also compared to the legal Euro 5 and Euro 6 emission limits, even though these do not apply to them. The type-approval results considered for these vehicles refer to the FTP (Federal Test Procedure) cycle, which is the regulated cycle in the US.

This improves the readability of complex charts and guides the reader through the different levels of detail.

» *Transparency*. All the relevant emission signals are reported. Detailed results for all trips are provided in Part 2 of this report, both in graphic and tabular form.

4.2 DISTANCE-SPECIFIC EMISSION FACTORS

The majority of the emission factors reported in our analysis are distance-specific (or "distance-based"), meaning that they are given in terms of mass of pollutant emitted per distance driven. This is the usual way in which legal emission limits are expressed.[7]

4.2.1 Raw average emission factors

Distance-specific emission factors can be easily derived by dividing the cumulative emissions of a pollutant (measured by the PEMS system) by the total distance covered (which is in turn derived from the GPS velocity signal). This can be done for individual PEMS trips, or for a collection of several PEMS trips from the same vehicle. If no data exclusions are performed, thus derived "raw" (all-inclusive) emission factors are representative only of the driving conditions that produced them. Unlike emission factors derived from repeatable chassis dynamometer tests, these emission factors will exhibit substantial variability because they are affected by the trip composition (e.g., the share of urban or highway driving), the thermal history of the engine and after-treatment system (i.e., whether the vehicle was cold- or warm-started), environmental conditions (e.g., temperature, ambient pressure, rain, altitude, or road gradient), traffic conditions, and other uncontrolled sources of variability. As a general rule, on-road emission factors will be higher than those derived from chassis dynamometer experiments, because most on-road sources of emission variability tend to push emission levels upward.[8]

The key issue is *whether measured on-road emissions levels stay reasonably close to the laboratory-based values*. A usual way of comparing on-road emission levels to laboratory-based emission limits is to calculate the so-called conformity factor (CF), which is the ratio of (distance-specific) on-road emissions to a reference (also distance-specific) emission limit. For the purposes of this report, we will compute the CF of measured emissions to Euro 6 emission limits.

4.2.2 Situation-specific emission factors

One of the main advantages of PEMS testing is the ability to assess the influence that real-world factors have upon emissions. The usual way of doing this is to design test campaigns in such a way that a certain real-world influencing factor is assessed in a "one-at-a-time" fashion. For example, one can plan a certain route to include a large share of uphill driving, or instruct the driver to drive the same route several times with more or less aggressive behavior, and evaluate the resulting impact of these qualitative variations upon emission levels.

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7 Note that the distance in legal emission limits refers to the fixed distance of the driving cycle, whereas for PEMS it is the (variable) trip or data window distance that serves as the basis for the calculation of the emission factors.

8 An exception to this is the influence of cold-start emissions, because most regulated cycles are shorter than the typical PEMS trip (which usually lasts about an hour). Therefore, the relative impact of cold-start emissions on the average emission factors derived for a PEMS trip is lower than, for example, the contribution of cold-start emissions to type-approval results over NEDC.

This approach was not possible in our study, because the experimental data came from different studies with different experimental designs that were for the most part beyond the control of ICCT. It is, however, possible to filter or "bin" the data according to different criteria and then develop distance-specific emissions that let us assess the impact of different operating conditions. In this report, the emission signals were binned using the signals related to instantaneous velocity and acceleration, estimated road gradient, and measured temperature (either exhaust or coolant temperature, depending on availability). These binning criteria were applied to calculate situation-specific emission factors, which can then be plotted (see, e.g., Figure 3) or listed in tabular form to visualize the effect of real-world factors upon emission rates.

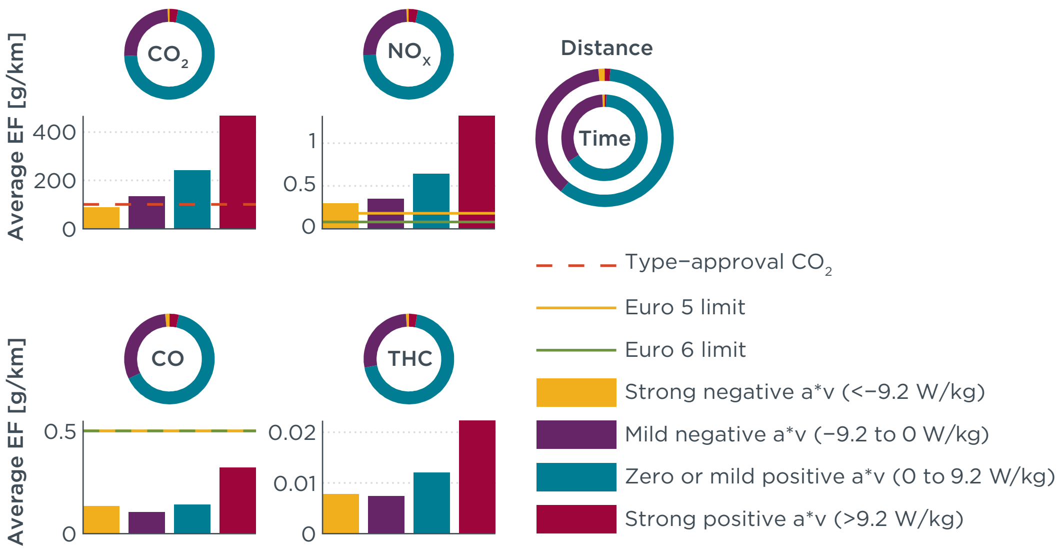

Figure 3: Example visualization of situation-specific emission factors (binning by acceleration*velocity)

The binning criteria used for the derivation of these emission factors are summarized in Table 3 and defined as follows:

- *Velocity*. The instantaneous velocity provides a very simple and useful characterization of the driving situation. The datasets were filtered using the GPS velocity signal, leading to four velocity bins: Idling (velocity below 2 km/h), Urban (2 to 50 km/h), Rural (50+ to 90 km/h) and Motorway (above 90 km/h). For practical reasons, the Idling section of the trips was defined in terms of vehicle speed instead of actual engine speed, and no distance-specific emission factors were derived for this particular bin.[9]
- *Acceleration*velocity (a*v)*. If we multiply the instantaneous GPS velocity signal by the (calculated) instantaneous acceleration, we obtain an *a*v* signal [in m^2/s^3, or W/kg], which is an approximation of instantaneous, mass-specific power. This signal adopts negative values during decelerations. The set point of 9.2 W/kg was selected as the threshold between "mild" and "strong" a*v because this is the maximum value for the NEDC time-velocity trace.
- *Road gradient*. The road gradient or steepness imposes an additional load on the engine that is proportional to the mass of the vehicle and to the sine of the

9 Instead, idling emission rates were calculated in terms of mass of pollutant emitted per unit of time.

gradient angle Θ (this load is negative for downhill driving, when $\Theta<0$). The road gradient [in %] was estimated from the GPS altitude and velocity signals. In order to have a robust calculation of road gradient (i.e., one that is less affected by noise in the input signals), the gradient was initially calculated using moving 500-meter windows. These windowed gradient values were then mapped back (see Part 2 of this report) to 1 Hz to produce a signal that is a smoothed estimator of instantaneous road gradient.

- *Exhaust gas/engine coolant temperature*. Monitoring temperature signals is useful to determine the thermal history of the engine block and the aftertreatment system. The emissions of NO_x are especially sensitive to exhaust temperature because a minimum temperature threshold is required by both SCR and LNT systems to perform adequately, and also because engine-out NO_x emissions rise quickly as exhaust temperature increases.
- In addition to the one-at-a-time application of the binning criteria, we also applied them in combination to derive emission factors for two different categories of "undemanding" driving. This was done by excluding the driving situations that would in principle lead to elevated emission levels[10] (e.g., high road gradient, strong positive acceleration*velocity). These undemanding emission factors are therefore not representative of real-world driving, but they were nonetheless derived to determine "best behavior" baseline emission levels for the test vehicles under favorable conditions.

10 This is the only instance in which data exclusions were performed for the purposes of our analysis. The amount of data that were excluded from each trip to derive the "undemanding" emission factors is reported in Part 2 of this report.

Table 3: Filtering criteria for the derivation of situation-specific emission factors

A) Single binning (one criterion at a time)				
Criterion	**Calculation[1]**	**Set points for the bins**	**Bin descriptor**	**Color ID**
Velocity [km/h]	From GPS velocity	Velocity <2 km/h	Idling	Idle
		2 ≤ Velocity < 50 km/h	Urban	Urb.
		50 ≤ Velocity < 90 km/h	Rural	Rur.
		Velocity ≥ 90 km/h	Motorway	Mwy.
Acceleration* velocity (a*v) [W/kg]	From GPS velocity	a*v < -9.2 W/kg	Strong negative a*v	▽▽
		-9.2 ≤ a*v < 0 W/kg	Mild negative a*v	▽
		0 ≤ a*v < 9.2 W/kg	Zero or mild positive a*v	△
		a*v ≥ 9.2 W/kg	Strong positive a*v	△△
Road gradient [%]	From GPS velocity and GPS altitude	Gradient < -4 %	Strong downhill	▽▽
		-4 ≤ Gradient < -1 %	Mild downhill	▽
		-1 ≤ Gradient < 1 %	Pretty flat	□
		1 ≤ Gradient < 4 %	Mild uphill	△
		Gradient ≥ 4 %	Strong uphill	△△
Exhaust gas/coolant temperature [°C]	From tailpipe meas./ECU readout	Temperature < 10th percentile for the trip	Cold temperature	Cold
		10th ≤ Temperature < 90th percentile	Medium temperature	Med.
		Temperature ≥ 90th percentile for the trip	Hot temperature	Hot

B) Combined filtering (several criteria applied concurrently)			
Combination	**Filtering**	**Descriptor**	**Color ID**
Undemanding driving 1	Data are binned by velocity. Only points with motorway speed below 120 km/h are included. Likewise, only the points in the “Pretty flat,” “Medium temperature” and “Mild negative a*v” or “Zero or mild positive a*v” bins are included.	Undemanding Urban 1	Urb.
		Undemanding Rural 1	Rur.
		Undemanding Motorway 1	Mwy.
Undemanding driving 2	Same as “Undemanding driving 1”, but including the “Mild uphill” and “Mild downhill” bins.	Undemanding Urban 2	Urb.
		Undemanding Rural 2	Rur.
		Undemanding Motorway 2	Mwy.

1) See Part 2 of this report for detailed emission factor calculation procedures.

4.3 CO_2 WINDOW ANALYSIS

It is unrealistic to expect that a vehicle certified to a certain emission standard will stay below the certified limits under all driving conditions. Even during type-approval tests, emissions hit several peaks at given points of the driving cycle in which they can be several times above the emission limit. But this does not prevent their average emissions throughout the cycle from meeting the relevant emission limits. Likewise, it is acceptable for vehicles tested with PEMS to register points at which the emission limits are exceeded, but at the same time, their average emissions over long distances (i.e., distances comparably longer to those of type-approval cycles) should be kept under control.

PEMS tests are performed by driving the instrumented vehicles in real (unpredictable) traffic and driving conditions. Therefore, it is not possible to follow a standard driving cycle (predetermined time-speed profile). However, it is possible to relate PEMS test results to cycle values by selecting a fixed reference magnitude pertaining to the test cycle and subsequently windowing PEMS data according to this magnitude. For example, knowing that NEDC covers a fixed distance of 11.02 km (in a fixed time of 1,180 seconds), we could divide a given PEMS dataset in bins (or data windows) to have that same distance (or duration) and compute the total emissions over these windows. Since the windows would then share a common characteristic with a reference cycle, it would be possible to compare windowed emissions to the known cycle results or emission limits and have a meaningful estimation of the influence of real-world driving conditions.

For the purposes of this report, we have chosen to divide our data into windows using type-approval CO_2 emission values as the reference magnitude. By selecting CO_2 as a reference, the data window size is not defined in terms of distance or time, but rather by the amount of CO_2 emitted over them. We will also use *moving data windows*,[11] meaning that the window calculations are conducted from the beginning of the PEMS dataset with a time increment equal to one second (as is done, e.g., in Weiss et al., 2012). An advantage of using moving data windows is that it makes it possible to derive thousands of windows from a single data trip, which can then be use to approximate the statistical distribution of distance-specific emissions. If the size of the windows is large enough, data windowing also provides a more robust calculation of distance-specific emissions (i.e., one that is little affected by potential time misalignments between the GPS velocity signal used to calculate trip distances and the mass emission signals) than other approaches that use smaller data bins.

4.3.1 CO_2 normalization

In some charts found in Part 2 of this report, we have applied a CO_2 normalization that is overlaid to the actual, measured emission results. This normalization entails a smooth weighting of windowed emissions data based on the ratio of their distance-specific CO_2 emissions to the corresponding type-approval value (eq. 1). For example, if a window with highly transient driving or steep uphill driving has distance-specific CO_2 emissions that are 30% above the type-approval value for the vehicle, the corresponding CO_2 normalization factor for that window would be 1/1.3 ≈ 0.77, and the emissions of all other pollutants for that window would be weighted down by approximately 23% after the CO_2 normalization.

$$CO_2 \text{ normalization factor}_i = \frac{CO_2 \text{ type-approval [g/km]}}{CO_2 \text{ window}_i \text{ [g/km]}} \qquad \text{eq. (1)}$$

The rationale behind the fuel normalization is that, by weighting emissions according to a reference distance-specific CO_2 value, we can mitigate the variations in the emission profile of the vehicle caused by several real-world sources of emissions variability that have a direct impact on fuel consumption (and therefore on CO_2 emissions). In particular, the CO_2 normalization would cover the effects of velocity, highly transient driving, road gradient, and temperature. An example of the effect of the CO_2 normalization upon a single trip (see yellow-green line) is provided in Figure 4. Note that the effect of normalization is to bring the emission levels of CO_2 to the type-approval value, whereas for NO_X it has the effect of weighting emissions down when the CO_2 emissions were above type

11 Moving CO_2 windows are used in European HDV regulations (EC, 2011; 2012), and they are also the basis for one of the PEMS data evaluation methods that will be further developed within the RDE-LDV working group.

approval and vice versa. On the other hand, Figure 4 is meant to illustrate the effect of normalization upon a collection of trips driven by the same vehicle over different routes. In this figure, the scatter of the results is reduced after CO_2 normalization (as are the average emissions of both NO_x and CO).

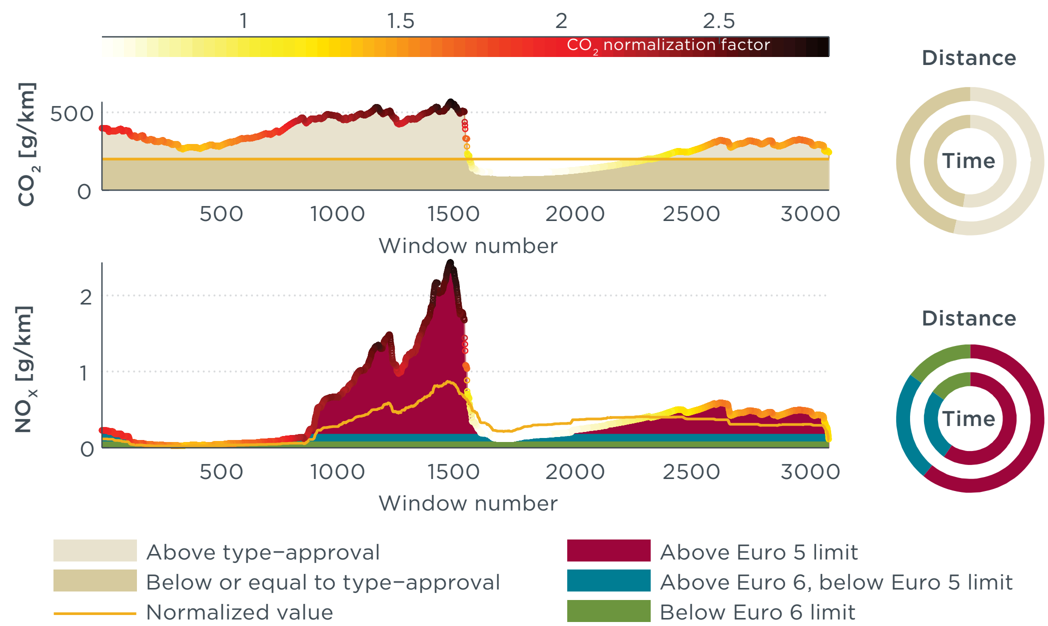

Figure 4: Example visualization of the CO_2 window analysis for trip B04 (with CO_2 normalization)

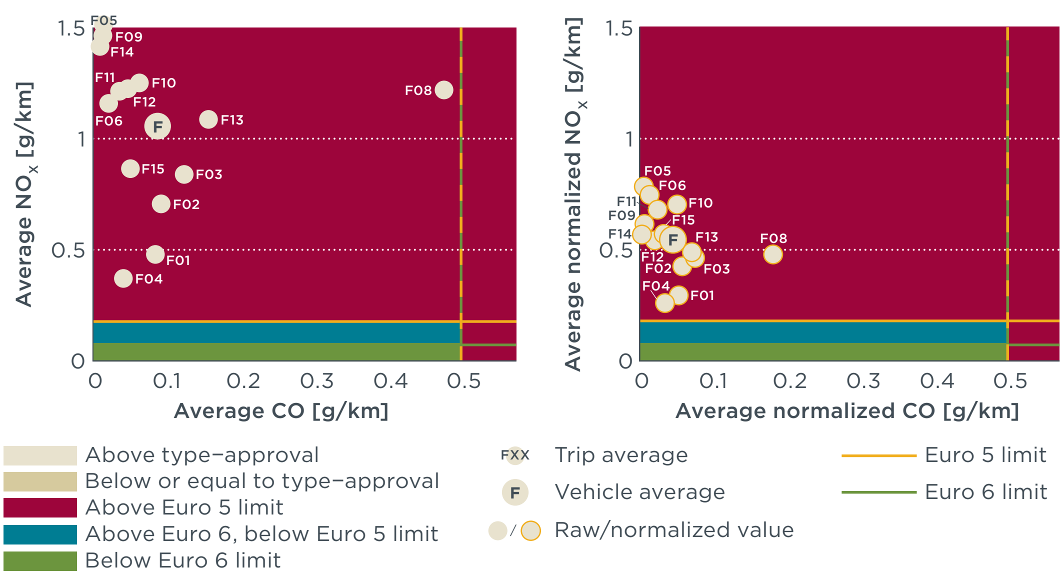

Figure 5: Effect of CO_2 normalization upon the emission results of a collection of trips for Vehicle F (both the scatter and the average emission levels are reduced)

A key advantage of the CO_2 normalization is that it works both ways, meaning that it can also apply a weighting factor higher than unity whenever the distance-specific CO_2 emissions over a particular window lie below the type-approval value. However, more often than not, real-world CO_2 emissions will be higher than at type approval, and the general effect of the normalization will be to lower the emission values. Therefore, the merit of normalization is not to produce a “corrected” emissions value (the measured value being the closest approximation to the actual emission value that ends up in the atmosphere), but to be able to take dissimilar PEMS datasets and reduce the scatter in the results. This can be useful if, for instance, we want to compare the performance of two vehicles tested under different conditions (e.g., with completely different route designs, driver behavior, or traffic conditions).

4.4 INSTANTANEOUS EMISSIONS ANALYSIS

In some instances—for example, when studying the causes of emission events—it is helpful to look into the emission profile of the vehicle under study with a high temporal resolution. Figure 6 presents an example of the highest level of detail with which we will assess PEMS data. In this figure, the instantaneous mass emissions of NO_X (in g/s, with 1 Hz time resolution) are plotted once for each of the filtering criteria listed in Section 4.2.2. Then, the individual data points are colored according to the filtering criteria using the same color scheme applied for the situation-specific emission factors. With this type of data visualization, we can observe the emission peaks that occurred throughout a PEMS trip and investigate the driving conditions that originated them (and even observe which real-world sources of variability were acting concurrently). For example, in Figure 6 we can see that the high NO_X emission rates around the 1,500th second of the trip are probably due to the positive road gradient and the medium speed conditions. Towards the end of this section of the trip, the exhaust temperature was quite hot, staying above the 90th percentile value for the whole trip (227°C). This type of chart was produced for each PEMS trip and measured pollutant. The complete collection of charts assessing the instantaneous emission rates can be found in Part 2 of this report.

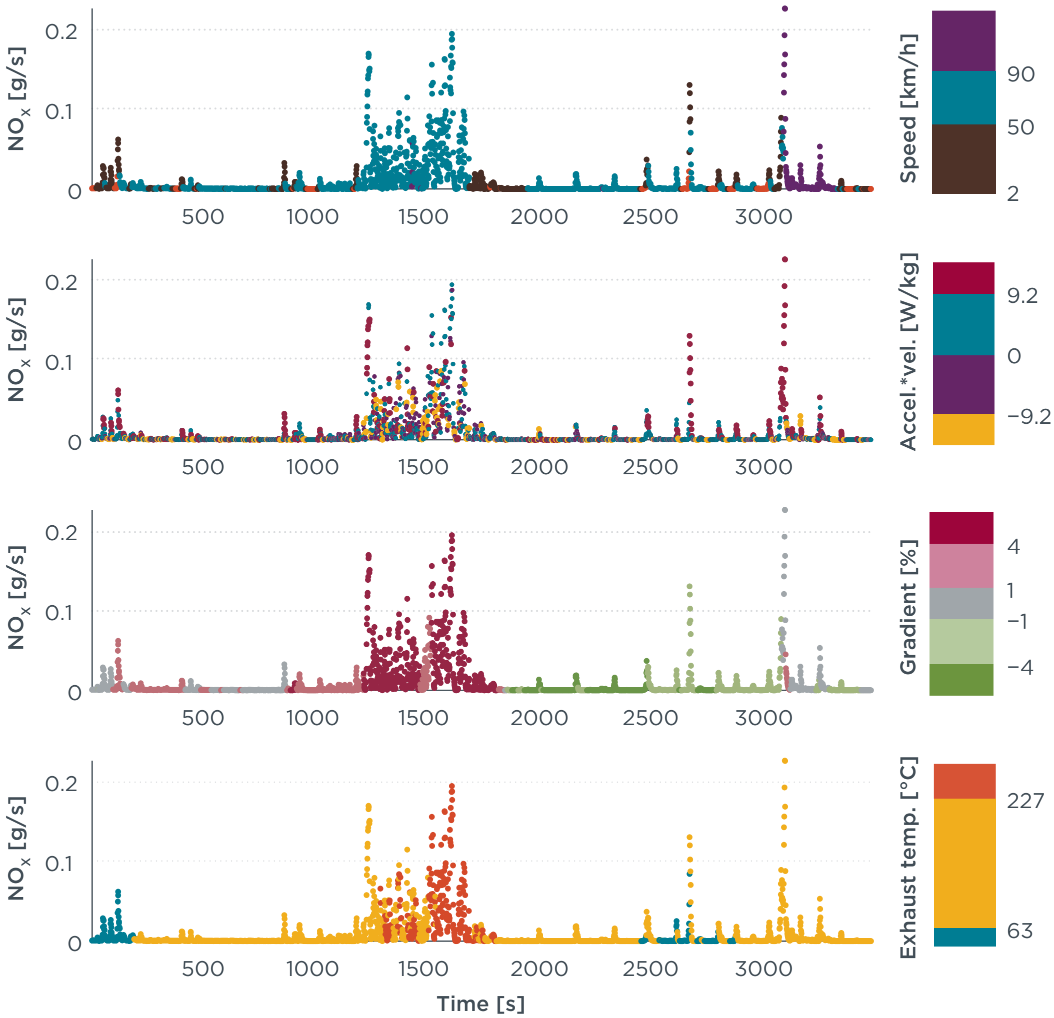

Figure 6: Example visualization of instantaneous on-road emissions discerning the driving situation (Trip B04)

5 RESULTS AND DISCUSSION

In this section, we will not report the results of our analysis in their entirety. Instead, we will focus on the aggregate results (e.g., average emission levels, or qualitative influence of driving conditions upon emissions) and use a few selected charts to structure our discussion. The results not covered in this part of the report are covered in Part 2, which includes all of the relevant charts and tables found in this document, plus detailed charts that cover individual PEMS trips in fine detail.

The discussion of the results found in this report will be strongly focused on NO_X emissions, because NO_X is by far the pollutant with the highest on-road emission levels compared with the regulated limit. Real-world CO_2 emissions are also discussed in relation to the gap between type-approval and real-world emissions, although a more detailed discussion on this topic can be found in Mock et al., 2013. Also of relevance are the emissions of CO, because they typically exhibit a trade-off with NO_X.

5.1 RESULTS

In this section we cover some of the most relevant aggregated results (i.e., pertinent to collections of trips or vehicles). These results include average distance-specific emission factors and situation- and distance-specific emission factors by vehicle and trip. The complete detailed results by individual trip and vehicle, in both graphical and tabular form, are included in Part 2 of this report.

5.1.1 Raw distance-specific emissions for all vehicles

In Figure 7 we show a first graphical representation the "raw" average distance-specific emissions of NO_x and CO for all the vehicles covered in all the experimental campaigns. These raw average emission values are presented in context with Euro 5 and Euro 6 emission limits and with the on-road CO_2 emissions (plotted as the percentage of type-approval values for individual vehicles). NO_X results are plotted on the y-axis due to their significance for Euro 6 and Tier 2 bin 5 /ULEV II Diesel passenger cars. Even though CO emissions stayed consistently low (below the Euro 5/6 limit of 0.5 g/km), these are also plotted because of their known trade-off with NO_X.

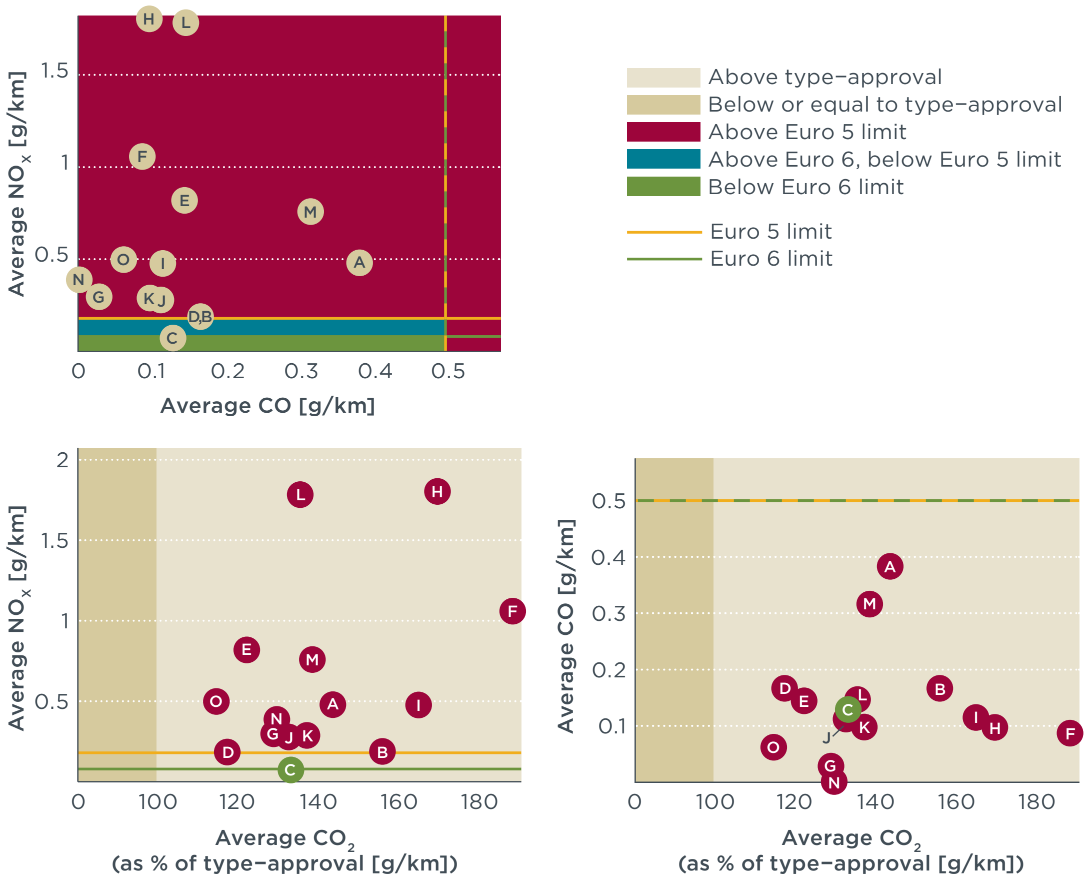

Figure 7: Average raw emission factors of NO_X, CO and CO_2, by vehicle

The emission values reflected in Figure 7 are tied to the particular driving and environmental conditions of the trips that generated them, which differ from vehicle to vehicle.[12] Also, the amount of data behind each one of the vehicle averages can differ substantially. Nonetheless, this chart gives a first rough approximation of the on-road compliance picture for the vehicles under test, and it shows that the average on-road NO_X emission levels for all Euro 6 and Tier 2 bin 5/ULEV II certified vehicles were above Euro 6 certification limits, except for Vehicle C, for which only one PEMS trip was available (and that trip did not include significant road grade). The emission levels of most vehicles are also above the more lenient Euro 5 NO_X emission limits applicable to the previous generation of vehicles. Some vehicles (e.g., D, B, J, or K) are reasonably close to on-road compliance with Euro 5 NO_X emission limits, but others exhibit a much poorer performance (especially Vehicles H and L).

The on-road CO emission performance was consistently very good, with all of the test vehicles having average emission levels below the Euro 5/6 limit.

The average, real-world CO_2 emissions of all test vehicles were above their corresponding type-approval values. Interestingly, the vehicles that were driven more aggressively (if we take the ratio of on-road CO_2 emissions to type-approval CO_2 values as a

12 Summaries of the average driving conditions for each *vehicle* are in Table 4, and for each *trip* in Table 5. The specific driving conditions for each trip, as well as the average conditions for each individual vehicle and other detailed information, can be found in Part 2 of this report.

preliminary proxy for demanding driving conditions) were not necessarily the ones with the worst on-road NO_x performance (see, for example, the NO_x and CO_2 performance of Vehicle I in Figure 7). If we look at aggregate metrics of driving dynamicity, such as the share of total driving time spent under "strong positive acceleration*velocity" or "strong uphill" driving, or the total distance share of urban or highway driving (plotted in Figure 8), we also see that it is difficult to link these metrics to elevated average emissions from the different vehicles. For example, Vehicle B has the largest time share of both "strong uphill" and "strong positive acceleration*velocity" driving, which should make it one of the highest emitters of NO_x instead of one of the lowest. Therefore, we will have to dig deeper into the driving conditions to find a link between these and the emission behavior of the vehicles.

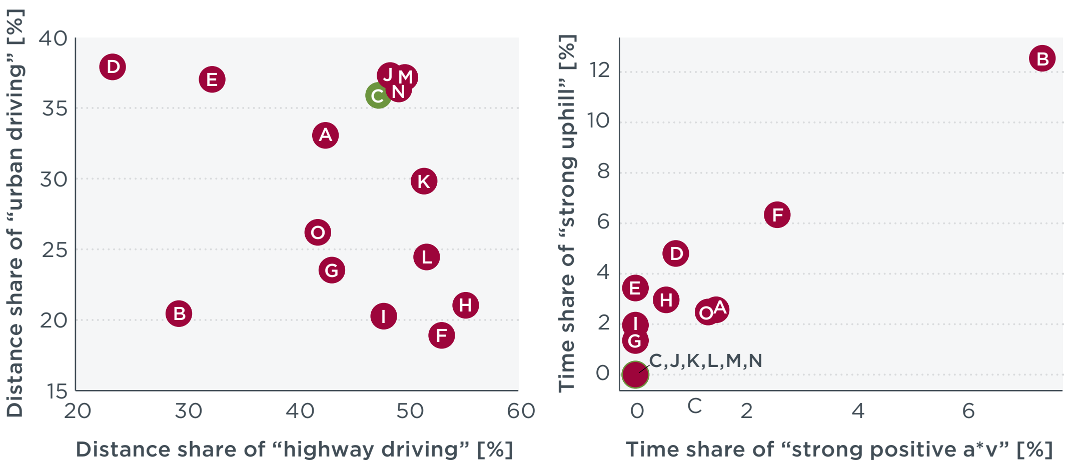

Figure 8: Distance share of "urban driving" and "highway driving", and time share of "strong uphill" and "strong positive acceleration*velocity", by test vehicle

5.1.2 Characterization of the PEMS trips

The time and distance shares plotted in Figure 8 provide a preliminary but insufficient characterization of the driving conditions experienced by the test vehicles. Whenever on-road emission levels are characterized as trip or vehicle averages, it is good practice to report the time-speed profile, the shares of driving distance or time spent under urban/rural/motorway driving or other metrics that allow a quick characterization of the trip. In this report, we are providing these results and a detailed characterization of individual trips that includes the second-by-second velocity profile, the calculated road gradient and the shares of trip time and trip distance (as % of the total trip duration and distance, respectively) spent in each one of the driving situations defined in Table 3 of Section 4.2.2. Summaries of these distance shares are presented for all vehicles in Table 4, and for all trips in Table 5. These tables also include raw EFs of CO_2, NO_x and CO.

By looking at these tables, which are also included in Part 2 of this report, it is possible to identify trips with unusual compositions—e.g., with a large share of uphill driving, or no highway driving—and observe the effect upon raw emissions.

Table 4: Key raw emission factors and distance shares by vehicle (all trips)

	Raw EFs			Trip distance shares [%]												
	[g/km]	[mg/km]		Velocity				Acceleration*velocity				Gradient				
	CO_2	NO_x	CO	Idle	Urb.	Rur.	Mwy.	▽▽	▽	△	△△	▽▽	▽	□	△	△△
Vehicle A	288	482	388	0.0	33.1	24.3	42.6	1.4	35.5	61.1	2.0	2.4	25.5	44.2	26.3	1.6
Vehicle B	294	235	207	0.1	20.5	50.1	29.4	10.8	27.3	52.4	9.5	11.8	19.3	41.2	15.9	11.7
Vehicle C	160	72	129	0.0	35.9	16.7	47.4	0.0	36.4	63.6	0.0	0.0	6.4	88.4	5.2	0.0
Vehicle D	184	171	159	0.0	37.9	38.7	23.4	1.1	43.3	55.0	0.6	4.2	17.2	57.6	17.6	3.4
Vehicle E	197	819	145	0.0	37.0	30.6	32.3	0.0	34.5	65.5	0.0	2.6	25.7	42.8	24.0	5.0
Vehicle F	270	908	67	0.1	18.9	27.9	53.1	2.4	42.2	52.6	2.7	5.2	19.4	46.4	21.8	7.2
Vehicle G	148	294	28	0.0	23.5	33.3	43.2	0.0	29.3	70.7	0.0	1.3	22.1	53.1	22.5	0.9
Vehicle H	254	1809	86	0.1	19.2	28.0	52.7	1.5	40.8	56.4	1.2	5.6	20.5	51.5	17.5	4.9
Vehicle I	175	438	130	0.0	39.5	29.2	31.3	2.0	27.9	69.2	0.9	4.3	22.7	45.7	21.5	5.8
Vehicle J	143	279	113	0.0	37.3	14.2	48.4	0.0	29.7	70.3	0.0	0.0	6.5	87.4	6.1	0.0
Vehicle K	165	289	98	0.1	29.8	18.6	51.5	0.0	34.5	65.5	0.0	0.0	6.9	87.3	5.8	0.0
Vehicle L	210	1783	147	0.1	24.5	23.8	51.7	0.0	41.9	58.1	0.0	0.0	11.0	79.9	9.1	0.0
Vehicle M	151	758	316	0.0	37.2	13.0	49.8	0.0	33.9	66.1	0.0	0.0	6.5	88.6	4.9	0.0
Vehicle N	194	388	2	0.0	36.4	14.4	49.2	0.0	31.2	68.8	0.0	0.0	6.4	85.7	8.0	0.0
Vehicle O	152	504	61	0.0	26.2	31.9	41.9	0.0	35.9	62.2	1.9	1.0	22.7	54.0	20.8	1.6

Table 5: Key raw emission factors and distance shares by trip

	Raw EFs			Trip distance shares [%]												
	[g/km]	[mg/km]		Velocity				Acceleration*velocity				Gradient				
	CO_2	NO_x	CO	Idle	Urb.	Rur.	Mwy.	▽▽	▽	△	△△	▽▽	▽	□	△	△△
A01	281	502	343	0.0	39.1	28.5	32.5	0.0	34.1	65.9	0.0	2.5	25.4	42.0	29.1	0.9
A02	299	579	574	0.0	25.7	21.0	53.3	8.0	29.5	62.5	0.0	1.0	29.4	40.4	28.6	0.6
A03	280	378	254	0.0	45.9	24.6	29.5	0.0	39.8	60.2	0.0	0.3	26.4	43.4	27.8	2.1
A04	281	478	443	0.0	27.1	21.2	51.6	0.0	35.1	58.7	6.2	4.5	22.7	47.7	23.8	1.2
A05	292	467	308	0.0	33.5	34.8	31.7	0.0	36.2	58.1	5.7	6.3	23.5	43.7	25.1	1.5
A06	291	477	374	0.0	29.3	17.4	53.2	0.0	39.0	61.0	0.0	0.0	25.6	47.5	23.5	3.5
B01	234	48	0	0.0	7.0	14.4	78.6	0.0	23.2	76.8	0.0	2.1	21.0	72.6	4.3	0.0
B02	273	34	10	0.1	37.8	52.8	9.4	0.0	39.6	60.4	0.0	0.1	24.5	52.8	20.3	2.3
B03	318	108	0	0.1	33.0	46.3	20.7	15.5	25.9	45.1	13.5	2.7	18.2	62.6	14.4	2.1
B04	285	428	917	0.0	11.1	74.0	14.9	13.5	29.3	45.3	11.9	19.4	17.9	22.9	21.4	18.3
B05	284	377	90	0.0	10.3	73.1	16.6	15.8	28.7	41.3	14.1	20.4	18.0	24.4	19.1	18.1
B06	278	421	158	0.0	10.3	72.8	16.9	14.1	20.2	52.1	13.5	18.6	13.3	33.1	18.3	16.7
B07	428	33	160	0.3	61.2	16.8	21.8	14.5	29.7	45.3	10.4	10.4	23.8	29.9	19.0	17.0
B08	399	70	0	0.2	52.1	22.1	25.6	16.7	33.1	36.2	14.1	7.8	25.9	35.2	15.4	15.6
C01	160	72	129	0.0	35.9	16.7	47.4	0.0	36.4	63.6	0.0	0.0	6.4	88.4	5.2	0.0
D01	201	91	247	0.0	43.8	55.9	0.2	0.0	44.0	56.0	0.0	4.0	22.9	46.8	23.6	2.7
D02	146	127	44	0.0	11.8	36.1	52.0	0.0	45.0	55.0	0.0	0.2	11.4	77.3	11.1	0.0
D03	189	268	147	0.0	69.7	30.3	0.0	4.6	38.4	55.3	1.7	14.9	23.2	27.4	20.6	14.0
D04	152	187	189	0.0	46.2	53.8	0.0	0.0	35.1	64.9	0.0	4.2	20.0	48.6	25.1	2.0
D05	191	111	194	0.0	39.3	60.6	0.0	0.0	41.5	58.5	0.0	2.5	23.1	50.1	22.4	1.8
D06	416	132	378	0.0	17.2	33.0	49.8	0.0	57.1	42.9	0.0	0.0	11.5	76.1	11.8	0.6
D07	218	240	287	0.0	69.9	30.0	0.0	5.1	37.4	54.9	2.6	13.5	22.9	28.0	22.1	13.5
D08	233	132	135	0.0	44.4	54.1	1.5	0.0	52.6	47.4	0.0	2.4	22.4	52.1	22.3	0.8
D09	206	120	224	0.0	14.5	34.6	50.9	0.0	56.8	43.2	0.0	0.0	11.2	77.9	11.0	0.0
D10	207	341	235	0.0	74.7	25.3	0.0	5.0	37.3	55.3	2.5	14.9	21.3	29.6	20.6	13.6
D11	241	143	153	0.0	47.3	51.8	0.9	0.0	52.2	47.8	0.0	3.4	22.4	48.5	25.0	0.7
D12	164	189	73	0.0	12.5	32.0	55.5	0.0	44.7	55.3	0.0	0.0	9.4	80.6	10.0	0.0
D13	253	361	256	0.0	66.0	34.0	0.0	8.7	38.2	46.2	6.9	13.9	23.5	28.2	21.0	13.4
D14	174	202	174	0.0	48.6	51.3	0.0	0.0	41.8	58.2	0.0	2.7	21.3	49.7	25.2	1.1
D15	161	218	126	0.0	52.0	47.9	0.0	0.0	42.8	57.2	0.0	3.9	22.4	49.0	22.8	1.8
D16	177	194	114	0.0	46.9	53.0	0.0	0.0	41.2	58.8	0.0	2.7	21.6	51.3	23.3	1.1
D17	170	256	87	0.0	56.0	44.0	0.0	0.0	35.2	64.8	0.0	5.1	23.1	45.5	24.5	1.7
D18	145	246	47	0.0	45.7	54.3	0.0	0.0	42.7	57.3	0.0	2.7	21.8	49.2	25.5	0.8
D19	157	152	110	0.0	41.4	58.6	0.0	0.0	37.9	62.1	0.0	3.1	22.3	49.0	24.6	1.0
D20	149	115	156	0.0	13.2	29.6	57.2	0.0	44.7	55.3	0.0	0.8	10.6	78.9	9.5	0.3
D21	187	246	188	0.0	70.9	29.1	0.0	7.2	35.1	52.7	5.0	13.3	21.0	31.4	20.7	13.6
D22	139	92	125	0.0	14.9	29.5	55.6	0.0	42.8	57.2	0.0	0.3	11.1	77.1	11.5	0.0
D23	180	181	188	0.0	77.8	22.2	0.0	4.0	35.6	59.4	1.0	15.2	21.8	28.3	20.8	13.9
D24	147	118	136	0.0	15.5	29.3	55.2	0.0	42.9	57.1	0.0	0.0	10.0	80.2	9.7	0.0
D25	141	157	104	0.0	56.3	43.7	0.0	0.0	41.1	58.1	0.7	2.2	22.0	48.5	24.9	2.4
D26	180	183	220	0.1	71.3	28.7	0.0	4.4	37.1	57.1	1.4	13.9	20.2	31.1	19.9	14.9
E01	212	1088	135	0.0	41.5	28.0	30.5	0.0	37.9	62.1	0.0	1.9	25.9	41.7	24.4	6.0
E02	191	908	208	0.0	37.5	31.0	31.4	0.0	32.6	67.4	0.0	5.1	20.0	46.8	22.0	6.1
E03	192	919	171	0.0	38.2	27.9	33.9	0.0	33.4	66.6	0.0	1.1	27.8	42.0	28.1	1.1
E04	196	935	151	0.0	43.4	24.2	32.3	0.0	32.9	67.1	0.0	5.0	22.2	44.6	27.0	1.1
E05	189	813	110	0.0	34.0	33.6	32.3	0.0	32.6	67.4	0.0	0.8	24.2	45.7	23.2	6.2
E06	208	676	178	0.0	35.2	33.3	31.5	0.0	36.1	63.9	0.0	1.8	28.5	41.8	20.8	7.2
E07	197	674	148	0.0	35.6	31.4	33.0	0.0	34.0	66.0	0.0	7.3	21.5	42.9	23.4	4.9
E08	191	664	82	0.0	29.8	37.1	33.0	0.0	34.2	65.8	0.0	0.0	29.2	42.7	21.1	7.0
E09	197	695	120	0.0	38.0	28.9	33.1	0.0	36.8	63.2	0.0	0.0	31.6	36.9	25.6	5.9

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Table 5: Key raw emission factors and distance shares by trip

	Raw EFs			Trip distance shares [%]												
	[g/km]	[mg/km]		Velocity				Acceleration*velocity				Gradient				
	CO_2	NO_x	CO	Idle	Urb.	Rur.	Mwy.	▽▽	▽	△	△△	▽▽	▽	□	△	△△
F01	218	478	84	0.0	9.1	11.3	79.5	0.0	44.3	55.7	0.0	3.5	21.5	65.8	6.9	2.3
F02	261	706	92	0.1	25.1	20.3	54.4	0.0	47.2	52.8	0.0	0.0	14.8	72.6	12.6	0.0
F03	293	839	123	0.0	1.6	4.6	93.8	0.0	46.1	53.9	0.0	0.0	14.5	57.6	23.3	4.7
F04	209	370	41	0.0	1.3	3.5	95.1	0.0	42.2	57.8	0.0	3.0	16.5	55.5	21.3	3.7
F05	285	1515	13	0.1	13.9	22.7	63.4	0.0	44.7	55.3	0.0	0.0	19.9	24.3	40.7	15.0
F06	252	1160	20	0.0	9.5	64.8	25.7	0.0	41.7	48.4	9.9	2.5	31.6	24.0	35.8	6.0
F08	413	1220	476	0.3	66.2	29.1	4.5	0.0	47.2	52.8	0.0	0.0	26.0	59.5	13.3	1.2
F09	385	1464	13	0.3	66.5	33.2	0.0	0.0	47.9	52.1	0.0	0.0	15.2	65.8	18.6	0.3
F10	261	1251	62	0.0	15.8	70.4	13.8	10.9	33.0	46.5	9.6	17.7	18.6	27.0	19.5	17.2
F11	256	1213	35	0.1	16.5	71.3	12.2	10.5	33.2	47.0	9.2	18.3	18.3	27.6	19.0	16.8
F12	380	1224	46	0.3	54.7	34.4	10.7	0.0	48.9	51.1	0.0	5.3	19.5	46.2	26.6	2.3
F13	365	1086	156	0.4	60.5	39.1	0.0	14.6	32.2	40.5	12.7	7.6	18.3	44.3	24.5	5.3
F14	392	1415	9	0.4	59.3	17.2	23.1	0.0	53.2	46.8	0.0	5.9	29.5	34.1	17.4	13.1
F15	278	865	50	0.2	28.1	28.2	43.5	0.0	49.3	50.7	0.0	0.0	24.3	65.5	6.1	4.2
G01	144	195	41	0.0	12.2	36.7	51.0	0.0	33.6	66.4	0.0	0.8	22.0	53.0	23.2	1.0
G02	153	335	4	0.1	16.9	29.3	53.7	0.0	26.8	73.2	0.0	1.4	22.6	52.4	23.4	0.3
G03	141	281	15	0.0	14.8	33.7	51.5	0.0	26.7	73.3	0.0	1.5	21.4	52.4	24.1	0.6
G04	139	275	59	0.0	34.5	33.8	31.6	0.0	32.7	67.3	0.0	0.5	23.1	53.4	21.4	1.5
G05	152	349	17	0.1	35.1	32.5	32.3	0.0	27.0	73.0	0.0	1.5	21.8	53.9	21.5	1.3
G06	161	347	37	0.1	34.9	33.6	31.5	0.0	29.0	71.0	0.0	2.0	22.2	53.9	20.8	1.2
H01	242	2384	16	0.0	9.2	15.3	75.5	0.0	41.8	58.2	0.0	0.0	16.2	57.2	22.4	4.3
H02	259	2253	110	0.0	10.4	17.1	72.4	0.0	40.2	59.8	0.0	4.8	22.9	57.4	14.9	0.0
H03	218	991	181	0.1	8.6	31.5	59.9	0.0	44.4	55.6	0.0	3.3	24.2	55.8	16.7	0.0
H04	209	1723	4	0.0	1.0	2.9	96.1	0.0	42.3	57.7	0.0	5.0	25.0	51.6	15.0	3.4
H05	203	721	192	0.1	5.7	12.1	82.2	0.0	44.2	55.8	0.0	2.4	20.7	65.2	9.7	2.0
H06	261	1373	164	0.1	34.9	31.1	33.9	0.0	38.8	61.2	0.0	1.9	9.9	63.0	22.9	2.2
H07	327	1547	178	0.5	63.3	27.5	8.7	0.0	45.6	54.4	0.0	0.0	25.3	57.7	15.1	1.9
H08	397	1822	215	0.4	81.2	18.4	0.0	0.0	42.1	57.9	0.0	0.0	18.8	63.9	16.0	1.4
H09	303	2992	26	0.1	15.6	70.7	13.6	8.2	32.4	53.4	6.1	16.4	20.6	25.8	20.6	16.6
H10	248	2531	16	0.1	13.5	74.8	11.6	8.6	35.2	48.6	7.7	17.6	18.9	24.7	21.5	17.2
H11	318	2126	46	0.4	56.0	28.9	14.7	0.0	45.6	54.4	0.0	6.1	24.6	43.4	23.1	2.9
H12	345	2883	66	0.4	58.4	29.1	12.1	0.0	40.4	59.6	0.0	4.4	18.5	51.9	21.3	3.8
H13	285	509	18	0.4	30.9	68.7	0.0	0.0	44.7	55.3	0.0	0.0	10.1	77.3	12.6	0.0
I01	178	477	115	0.0	20.3	31.8	47.9	0.0	28.1	71.9	0.0	0.6	20.2	55.9	22.8	0.4
I02	189	553	180	0.0	75.7	24.2	0.0	5.8	27.4	63.8	3.0	11.6	24.0	28.7	19.5	16.2
I03	169	474	171	0.0	76.9	23.1	0.0	5.4	26.9	65.5	2.2	11.5	24.1	30.4	17.7	16.3
I04	167	319	98	0.0	19.6	32.4	48.0	0.0	28.7	71.3	0.0	0.4	23.7	52.6	23.3	0.0
J01	143	279	113	0.0	37.3	14.2	48.4	0.0	29.7	70.3	0.0	0.0	6.5	87.4	6.1	0.0
K01	165	289	98	0.1	29.8	18.6	51.5	0.0	34.5	65.5	0.0	0.0	6.9	87.3	5.8	0.0
L01	210	1783	147	0.1	24.5	23.8	51.7	0.0	41.9	58.1	0.0	0.0	11.0	79.9	9.1	0.0
M01	151	758	316	0.0	37.2	13.0	49.8	0.0	33.9	66.1	0.0	0.0	6.5	88.6	4.9	0.0
N01	194	388	2	0.0	36.4	14.4	49.2	0.0	31.2	68.8	0.0	0.0	6.4	85.7	8.0	0.0
O01	149	523	40	0.0	15.5	28.8	55.6	0.0	35.0	65.0	0.0	0.9	23.2	52.0	22.8	1.0
O02	163	607	44	0.0	14.0	36.2	49.7	0.0	36.2	63.8	0.0	0.9	23.3	52.0	23.5	0.3
O03	147	409	77	0.1	36.3	30.4	33.2	0.0	35.3	54.1	10.7	2.6	22.0	53.6	19.7	2.0
O04	148	457	58	0.0	35.3	34.4	30.3	0.0	37.0	63.0	0.0	0.8	21.7	55.4	19.7	2.4
O05	150	495	94	0.1	35.7	29.2	35.1	0.0	36.0	64.0	0.0	0.0	22.8	57.9	16.8	2.6

In order to visualize the *dynamic driving conditions for the vehicles* under test, we can also plot their corresponding histograms of estimated instantaneous road gradient and acceleration*velocity. This is done in Figure 9 and Figure 10. From these figures, it is apparent that Vehicles C, J, K, L, M, and N (tested by Emissions Analytics; one PEMS trip available for each) were driven under milder conditions (flat roads, smoother accelerations) than the rest of the test vehicles. In fact, the in-use accelerations for these vehicles were far less aggressive than even the NEDC.

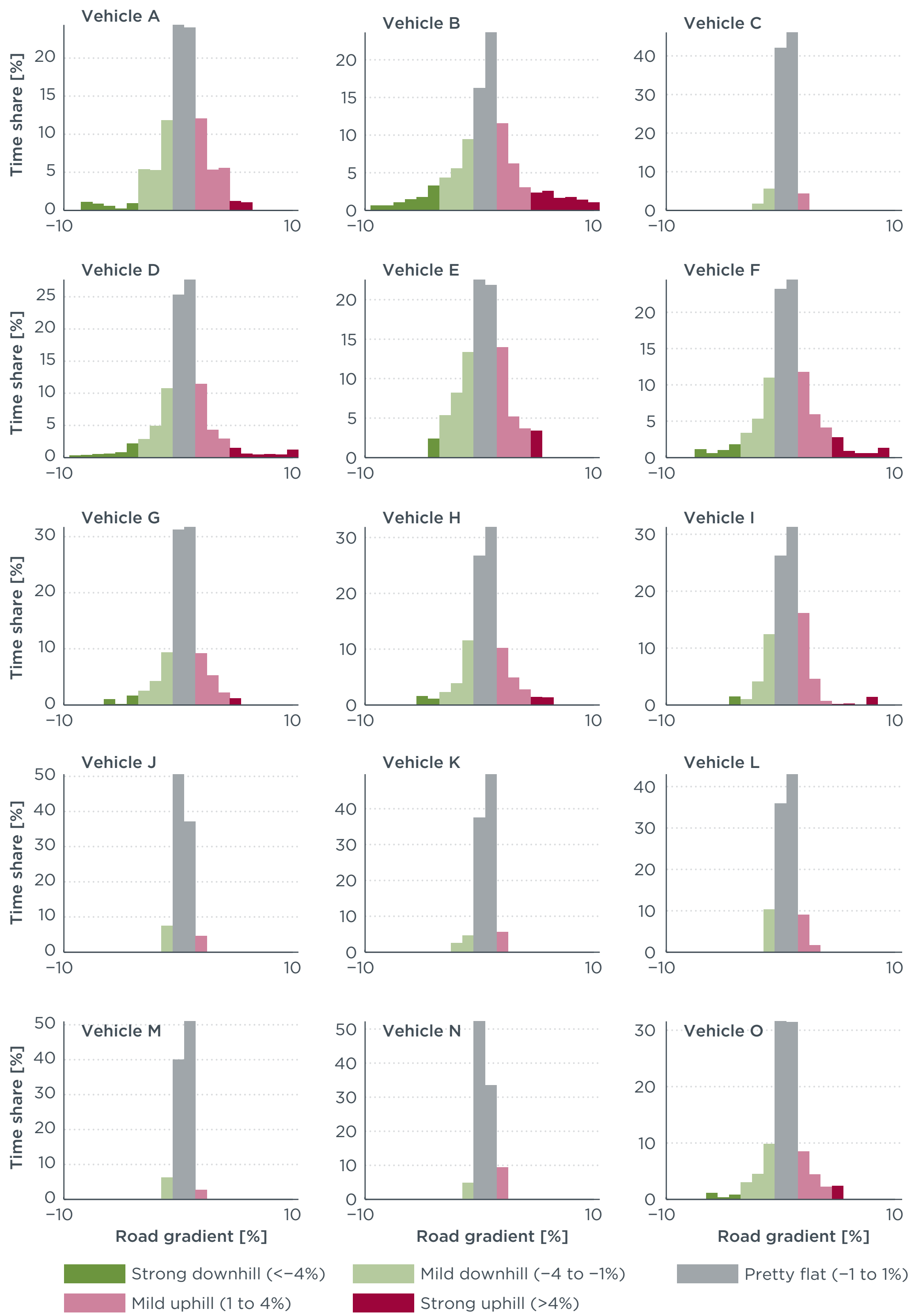

Figure 9: Road gradient histograms, by test vehicle

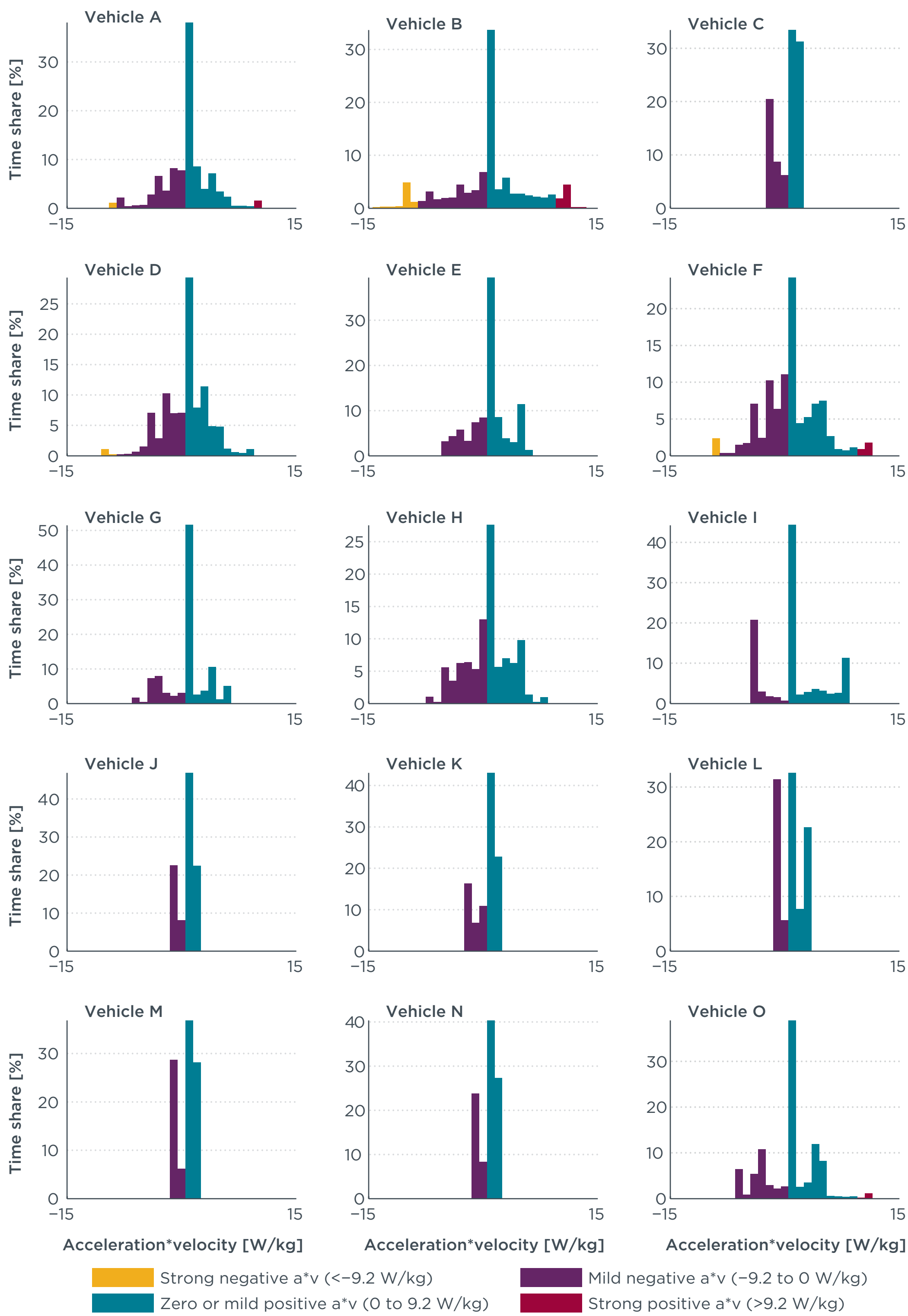

Figure 10: Histogram of acceleration*velocity, by test vehicle

5.1.3 NO_x emission factors by driving situation

Table 6 and Table 7 show the average distance-specific NO_x emission factors by vehicle and by individual trip corresponding to the velocity bins we have previously defined (and also to the "undemanding" situations). Conversely, Table 8 and Table 9 show the distance-specific NO_x emission factors—by vehicle and by individual trip—corresponding to the driving situation bins defined by the acceleration*velocity, road gradient, and temperature signals.[13] The information in these tables can be used in combination with Table 4 and Table 5 to gain a better understanding of the driving conditions that lead to high NO_x emissions, and of the relative frequency with which these situations occurred during the PEMS tests. For even more detailed information on the characteristics of individual PEMS trips and the emission behavior of the vehicles under test, please refer to the charts included in Part 2 of this report.

Table 6. NO_x EFs [mg/km] for all trips (binning by velocity)

	All driving conditions					Undemanding 1			Undemanding 2		
	Raw	Idle*	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.
Vehicle A	482	17	234	177	841	142	121	136	160	126	110
Vehicle B	235	12	206	331	81	65	27	31	77	68	26
Vehicle C	72	14	93	79	47	85	88	33	85	78	32
Vehicle D	171	35	253	130	82	247	112	62	227	126	62
Vehicle E	819	114	860	521	982	917	471	631	853	470	545
Vehicle F	908	183	1522	1083	533	1433	664	297	1429	792	426
Vehicle G	294	49	373	231	268	348	207	143	361	211	201
Vehicle H	1809	423	2166	1906	1471	1684	1232	1350	2054	1617	1380
Vehicle I	438	30	561	373	332	372	321	192	386	310	177
Vehicle J	279	12	362	317	199	360	277	163	364	288	151
Vehicle K	289	34	533	236	147	547	162	89	527	182	114
Vehicle L	1783	222	2350	1478	1544	2511	1250	1272	2346	1265	1290
Vehicle M	758	59	884	716	653	907	663	629	906	712	591
Vehicle N	388	45	558	297	271	545	277	165	558	275	172
Vehicle O	504	89	325	428	631	316	337	390	320	386	516

*Idling emissions in mg/min

13 Part 2 includes similar tables not just for the other pollutants measured during the PEMS tests (CO, THC and CO_2), but also for the filtering criteria. For example, it is possible to see the average gradient, velocity, acceleration*velocity, or temperature for each one of the gradient, velocity, acceleration*velocity or temperature bins, and also for the undemanding driving situations.

Table 7: NO_x EFs [mg/km] for all trips (binning by velocity)

	All driving conditions					Undemanding 1			Undemanding 2		
	Raw	Idle*	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.
A01	502	21	251	134	1115	146	71	54	179	131	80
A02	579	16	317	204	846	294	273	263	245	218	151
A03	378	15	178	183	843	100	99	98	132	131	59
A04	478	20	241	167	723	134	44	41	158	45	65
A05	467	14	264	175	991	158	45	92	150	60	196
A06	477	16	179	215	720	107	209	165	125	198	118
B01	48	10	160	95	28	15	5	22	11	6	16
B02	34	4	60	19	0	30	20	0	40	14	0
B03	108	17	184	66	55	140	40	161	127	49	78
B04	428	33	478	446	282	29	16	302	158	61	190
B05	377	13	463	438	45	139	34	12	169	152	23
B06	421	42	675	402	297	237	45	60	279	76	71
B07	33	1	41	14	21	3	38	13	10	15	11
B08	70	4	80	51	58	20	6	36	38	3	41
C01	72	14	93	79	47	85	88	33	85	78	32
D01	91	10	114	70	111	138	59	-	112	70	111
D02	127	19	305	132	80	306	109	81	281	128	81
D03	268	58	296	169	-	300	141	-	255	178	-
D04	187	30	250	125	-	287	123	-	244	121	-
D05	111	26	155	77	-	130	84	-	135	77	-
D06	132	56	245	62	23	169	50	25	151	49	24
D07	240	30	237	236	-	331	258	-	229	218	-
D08	132	18	188	85	23	181	86	1	156	82	23
D09	120	32	290	118	68	252	105	43	232	110	43
D10	341	80	344	264	-	389	286	-	333	255	-
D11	143	35	189	92	85	218	104	85	193	93	85
D12	189	25	377	158	160	339	126	102	360	157	102
D13	361	58	425	198	-	304	156	-	275	162	-
D14	202	12	261	142	-	303	124	-	238	140	-
D15	218	12	278	150	-	255	109	-	260	152	-
D16	194	7	275	119	-	261	110	-	282	119	-
D17	256	35	309	168	-	269	151	-	263	170	-
D18	246	20	328	172	-	335	161	-	307	183	-
D19	152	21	198	115	-	193	116	-	192	124	-
D20	115	38	250	141	64	235	113	57	248	142	60
D21	246	90	262	175	-	263	134	-	225	156	-
D22	92	8	182	114	55	173	79	48	161	106	48
D23	181	25	199	98	-	195	116	-	186	105	-
D24	118	6	202	124	91	191	117	68	199	113	65
D25	157	8	184	118	-	178	92	-	172	123	-
D26	183	52	198	111	-	237	127	-	195	121	-
E01	1088	238	1183	694	1092	1001	687	751	1078	652	525
E02	908	122	937	645	1067	1059	581	827	989	546	813
E03	919	126	914	637	1085	1000	546	875	943	546	766
E04	935	120	915	715	1052	932	701	759	890	686	853
E05	813	86	820	605	986	952	488	682	860	557	483
E06	676	89	706	366	906	751	347	430	622	318	320
E07	674	68	700	375	887	864	320	485	735	353	507
E08	664	53	792	316	912	810	268	484	725	316	353
E09	695	67	694	451	861	807	394	445	745	353	367

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Table 7: NO_x EFs [mg/km] for all trips (binning by velocity)

	All driving conditions					Undemanding 1			Undemanding 2		
	Raw	Idle*	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.	Urb.	Rur.	Mwy.
F01	478	485	1616	937	260	1564	1038	374	1488	968	328
F02	706	87	1070	946	429	883	1007	394	856	929	437
F03	839	152	2208	811	812	12694	1325	472	3523	958	694
F04	370	71	803	891	344	991	416	181	578	778	260
F05	1515	518	1593	1424	1439	1628	772	544	1465	1368	1074
F06	1160	200	2707	1078	736	2598	532	183	2289	800	274
F08	1220	61	1331	863	923	1381	437	-	1372	557	-
F09	1464	79	1634	1022	-	1439	759	-	1464	812	-
F10	1251	392	1768	1199	441	2569	421	338	2330	538	394
F11	1213	361	2059	1091	262	2191	558	238	2763	680	288
F12	1224	247	1255	747	914	1096	284	741	1060	371	610
F13	1086	84	1165	815	-	928	790	-	968	663	-
F14	1415	101	1665	1091	725	1576	635	808	1544	969	726
F15	865	94	1089	1246	424	586	350	283	863	1003	334
G01	195	32	224	189	182	216	190	95	204	167	102
G02	335	81	431	283	271	389	220	156	408	247	174
G03	281	36	412	249	248	399	227	131	392	218	213
G04	275	46	329	219	246	305	174	85	317	216	318
G05	349	44	406	212	386	378	196	301	399	196	416
G06	347	30	392	243	378	353	230	255	387	240	324
H01	2384	305	1822	2798	2352	1254	3149	1896	1605	2933	2001
H02	2253	659	3266	2383	1991	3471	1770	1868	3391	2383	1926
H03	991	108	1920	1049	796	2047	879	913	2094	1016	873
H04	1723	390	2846	2036	1691	-	1427	1593	2357	1900	1590
H05	721	54	1018	972	658	794	811	621	791	744	620
H06	1373	191	1720	823	1449	752	903	993	1770	892	1196
H07	1547	346	1592	772	822	1342	597	868	1435	649	794
H08	1822	580	1579	643	-	1402	508	-	1326	548	-
H09	2992	643	4509	2833	855	5879	2190	972	5706	2878	775
H10	2531	653	4016	2390	1026	4717	1612	1004	5116	2276	1018
H11	2126	400	2093	1259	2077	1475	890	1996	1734	1129	1817
H12	2883	713	2459	2709	2111	2401	3009	1874	2618	3001	2111
H13	509	58	564	429	-	543	380	-	581	362	-
I01	477	61	584	458	427	518	286	295	551	329	249
I02	553	34	617	346	-	274	266	-	300	296	-
I03	474	18	527	294	-	255	157	-	274	201	-
I04	319	6	493	330	238	439	403	88	487	333	103
J01	279	12	362	317	199	360	277	163	364	288	151
K01	289	34	533	236	147	547	162	89	527	182	114
L01	1783	222	2350	1478	1544	2511	1250	1272	2346	1265	1290
M01	758	59	884	716	653	907	663	629	906	712	591
N01	388	45	558	297	271	545	277	165	558	275	172
O01	523	87	411	451	567	408	371	409	393	388	451
O02	607	86	446	512	710	443	408	512	465	465	687
O03	409	33	271	365	579	233	272	181	245	323	379
O04	457	101	307	380	632	308	258	245	328	328	231
O05	495	117	290	392	670	281	337	170	279	395	409

*Idling emissions in mg/min

Table 8: NO_x EFs [mg/km] for all trips (other binning criteria)

	Acceleration* velocity				Gradient					Temperature		
	▽▽	▽	△	△△	▽▽	▽	□	△	△△	Cold	Med.	Hot
Vehicle A	162	267	567	1931	49	137	182	1341	793	580	166	1575
Vehicle B	192	157	183	790	52	77	112	216	1134	440	151	615
Vehicle C	-	45	87	-	-	85	71	81	-	204	68	65
Vehicle D	90	74	240	994	188	130	157	230	300	295	157	203
Vehicle E	-	369	1056	-	211	496	711	1249	1654	758	687	1439
Vehicle F	693	546	1150	2039	101	466	676	1326	2910	945	772	1666
Vehicle G	-	205	331	-	146	106	266	529	861	706	268	317
Vehicle H	1346	1451	2033	3991	150	917	1525	3118	5757	1556	1695	2604
Vehicle I	249	284	493	1369	156	197	354	588	1699	268	380	802
Vehicle J	-	167	326	-	-	218	277	373	-	129	281	279
Vehicle K	-	143	366	-	-	249	282	444	-	503	306	231
Vehicle L	-	882	2433	-	-	1475	1760	2367	-	3013	1672	2105
Vehicle M	-	475	904	-	-	548	764	936	-	717	766	739
Vehicle N	-	221	464	-	-	291	368	684	-	2790	375	436
Vehicle O	-	335	598	631	304	221	408	996	1539	413	432	795

Table 9: NO_x EFs [mg/km] for all trips (other binning criteria)

	Acceleration*velocity				Gradient					Temperature		
	▽▽	▽	△	△△	▽▽	▽	□	△	△△	Cold	Med.	Hot
A01	-	266	624	-	95	161	161	1326	517	724	151	1792
A02	162	337	747	-	97	148	298	1448	23	724	188	1751
A03	-	273	448	-	40	119	107	1027	721	485	127	1207
A04	-	271	450	1914	3	100	191	1491	682	520	194	2030
A05	-	244	459	1953	59	204	154	1305	1440	482	171	1390
A06	-	228	635	-	-	102	176	1438	835	513	157	1428
B01	-	18	57	-	0	5	64	9	-	802	13	59
B02	-	9	50	-	0	6	29	81	22	185	26	5
B03	34	49	129	235	84	123	105	106	80	349	95	69
B04	295	306	350	1176	43	211	242	230	1512	477	252	1660
B05	232	245	417	691	49	149	93	359	1376	248	231	1397
B06	294	362	245	1317	83	60	263	326	1503	4398	274	1379
B07	6	18	41	75	0	13	54	41	34	257	18	19
B08	24	40	87	150	30	29	62	120	126	358	55	70
C01	-	45	87	-	-	85	71	81	-	204	68	65
D01	-	37	133	-	5	82	96	102	97	133	86	95
D02	-	60	182	-	468	87	119	220	-	234	130	90
D03	108	164	346	537	267	140	250	308	461	357	231	577
D04	-	94	238	-	43	123	198	242	183	294	174	211
D05	-	57	150	-	18	103	118	115	124	252	99	92
D06	-	25	276	-	-	39	150	105	226	514	101	262
D07	93	122	309	794	188	183	334	259	167	506	219	173
D08	-	43	230	-	207	118	149	99	79	452	115	23
D09	-	38	228	-	-	86	121	146	-	283	97	175
D10	112	170	435	1288	251	199	453	373	369	539	313	448
D11	-	43	252	-	189	133	160	116	2	263	143	47
D12	-	81	276	-	-	119	179	338	-	206	159	312
D13	103	159	411	1464	407	369	362	324	353	506	334	456
D14	-	85	285	-	42	113	224	246	286	298	192	220
D15	-	100	307	-	73	154	199	336	356	377	210	201
D16	-	60	288	-	39	135	185	284	218	254	190	187
D17	-	132	323	-	200	226	222	309	970	296	227	482
D18	-	110	347	-	42	137	261	322	583	322	243	227
D19	-	68	204	-	142	94	145	214	256	221	151	122
D20	-	51	168	-	158	116	98	245	495	200	103	202
D21	82	123	291	872	179	164	278	316	257	408	220	338
D22	-	45	127	-	225	56	83	181	114	180	87	86
D23	58	102	236	296	152	107	193	222	246	282	158	319
D24	-	62	160	-	-	69	119	164	-	163	101	180
D25	-	82	207	325	65	92	143	224	408	232	154	132
D26	56	95	245	387	138	125	207	190	245	257	157	386
E01	-	498	1447	-	680	677	1037	1452	1866	2228	918	1520
E02	-	431	1138	-	64	519	791	1444	1852	422	806	1519
E03	-	449	1155	-	829	488	811	1417	3354	434	817	1539
E04	-	416	1190	-	46	603	865	1396	3281	660	834	1427
E05	-	382	1021	-	45	502	697	1161	1677	409	698	1455
E06	-	275	902	-	444	421	523	1105	1388	1145	485	1448
E07	-	262	887	-	173	536	562	1011	1407	449	546	1361
E08	-	271	869	-	-	401	506	1111	1381	624	528	1291
E09	-	337	903	-	-	385	577	1076	1442	413	559	1391

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Table 9: NO_x EFs [mg/km] for all trips (other binning criteria)

	Acceleration*velocity				Gradient					Temperature		
	▽▽	▽	△	△△	▽▽	▽	□	△	△△	Cold	Med.	Hot
F01	-	338	589	-	0	74	544	1102	1214	2442	462	269
F02	-	177	1180	-	-	412	706	1054	-	2213	692	439
F03	-	646	1004	-	-	411	659	1369	1740	724	777	1268
F04	-	252	456	-	23	97	227	692	2170	510	294	924
F05	-	1123	1832	-	-	343	1197	1634	3264	1560	1395	2005
F06	-	833	1272	1988	32	540	744	1710	3262	1595	976	2365
F08	-	182	2148	-	-	1021	1252	1427	1614	1073	1244	1184
F09	-	260	2571	-	-	1194	1311	2239	792	963	1340	2182
F10	826	1182	1281	1826	50	494	938	1417	3611	418	927	3763
F11	734	1001	1330	1924	32	400	1007	1779	3091	354	973	3312
F12	-	604	1817	-	423	1012	1310	1415	926	1586	966	2363
F13	339	533	1259	2793	367	773	1122	1499	989	526	919	1988
F14	-	425	2538	-	829	1095	1079	1687	2911	1713	1399	1389
F15	-	351	1363	-	-	1145	626	1161	2538	6302	813	992
G01	-	152	217	-	14	62	179	346	598	801	151	218
G02	-	212	380	-	204	139	313	566	1527	1293	298	332
G03	-	198	311	-	367	74	262	499	234	1525	252	328
G04	-	223	301	-	25	117	241	503	769	325	289	233
G05	-	232	392	-	76	98	312	662	1251	405	332	389
G06	-	239	391	-	34	158	297	671	1018	373	329	396
H01	-	2126	2570	-	-	1443	1959	3371	6461	2439	2177	3769
H02	-	1958	2452	-	962	1538	2310	3554	-	3586	2166	2567
H03	-	753	1182	-	87	643	973	1735	-	1564	1012	845
H04	-	1547	1851	-	141	799	1675	3311	4553	3257	1521	2965
H05	-	467	921	-	153	446	700	1151	2833	2493	649	724
H06	-	968	1630	-	207	444	922	2743	5170	2606	1345	1345
H07	-	1074	1944	-	-	1480	1387	1952	4081	1587	1494	1759
H08	-	1395	2134	-	-	1081	1984	1983	2556	2137	1512	3967
H09	1105	2571	3311	4955	45	629	2627	4982	6922	342	3023	5002
H10	1576	2172	2852	3217	86	555	2129	3950	6015	382	2354	5543
H11	-	1364	2765	-	242	1631	1921	3385	3333	1914	1845	3362
H12	-	2466	3165	-	126	3062	2822	3071	4980	934	3014	2293
H13	-	408	591	-	-	239	442	1135	-	1057	461	1161
I01	-	283	553	-	488	279	438	747	435	405	380	1129
I02	294	466	589	1080	198	132	277	610	1849	214	564	718
I03	200	328	514	1762	69	92	244	607	1609	97	341	2112
I04	-	170	379	-	345	218	321	415	-	530	294	378
J01	-	167	326	-	-	218	277	373	-	129	281	279
K01	-	143	366	-	-	249	282	444	-	503	306	231
L01	-	882	2433	-	-	1475	1760	2367	-	3013	1672	2105
M01	-	475	904	-	-	548	764	936	-	717	766	739
N01	-	221	464	-	-	291	368	684	-	2790	375	436
O01	-	316	634	-	552	187	477	957	731	1069	431	923
O02	-	413	718	-	104	225	508	1200	2509	799	564	857
O03	-	318	425	631	338	231	318	813	930	239	336	657
O04	-	279	561	-	100	247	319	933	1749	174	358	802
O05	-	336	584	-	-	225	384	998	2089	335	408	766

5.1.4 Windowed emission results

This section covers the results of windowing the mass emissions of CO_2, CO, and NO_x using the windowing principle described in Section 4.3. One of the biggest advantages of windowing the emissions data is that it is possible to extract a large amount of information from a single PEMS trip. For instance, if we consider all the trips for Vehicles A to O, it is possible to extract approximately 425,000 CO_2 windows, which are—to some extent—comparable to 425,000 type-approval test equivalents driven on the road.

5.1.4.1 OVERALL RESULTS (ALL TRIPS)

In this section, we show the results of extracting the CO_2 windows from all of the PEMS trips in our library of measurements and comparing the cumulative emissions over each window to the corresponding Euro 5/6 emission limits—for NO_x and CO—and to the type-approval CO_2 emission values—over NEDC for the European vehicles and over the FTP cycle for the US vehicles.

In Figure 11, the windows were sorted according to their level of compliance with the Euro 5 and Euro 6 limits, and also with the type-approval CO_2 values. The figure shows that roughly 75% of the windows had distance-specific CO_2 emissions above the type-approved value for the corresponding vehicle. Whereas the on-road compliance with Euro 5/6[14] CO emission limits was excellent, with only about 5% of the windows above the limit of 500 mg/km, the on-road emissions of NO_x were much worse, with only 10% of the windows staying below the Euro 6 limit of 80 mg/km.

If we plot the histogram of CFs for NO_x (Figure 12), we see that most of the windows had a conformity factor between 1 and 6. There are also a considerable number of windows with CFs between 10 and 30. Even though the absolute number of CO_2 windows with such high NO_x CFs is not very large, the absolute emission over such windows are between 10 and 30 times the legal limit, and so they concentrate a sizable share of all the NO_x emissions. *All in all, the average window had NO_x emissions equal to 7.1 times the Euro 6 limit*. On the other hand, if we plot the histograms of CFs for CO (Figure 13), we see that this pollutant was very well controlled for all measurement, with only a small fraction of the windows exceeding the Euro 5/6 limit, and doing so only by a small margin. In the case of CO, the average window had emissions equaling 0.32 times the Euro 6 limit.

14 Euro 5 and Euro 6 have the same emission limit for CO (500 mg/km over the NEDC cycle; see Table 1).

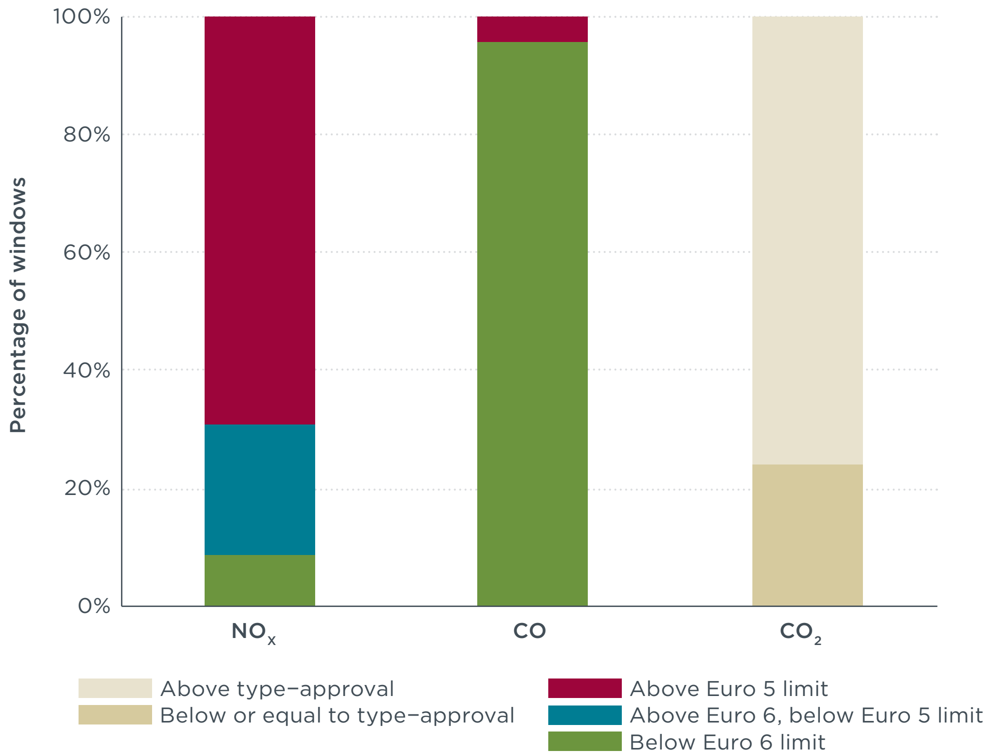

Figure 11: Evaluation of windowed emissions against Euro 5/6 emission limits and type-approval CO_2 values (all windows)

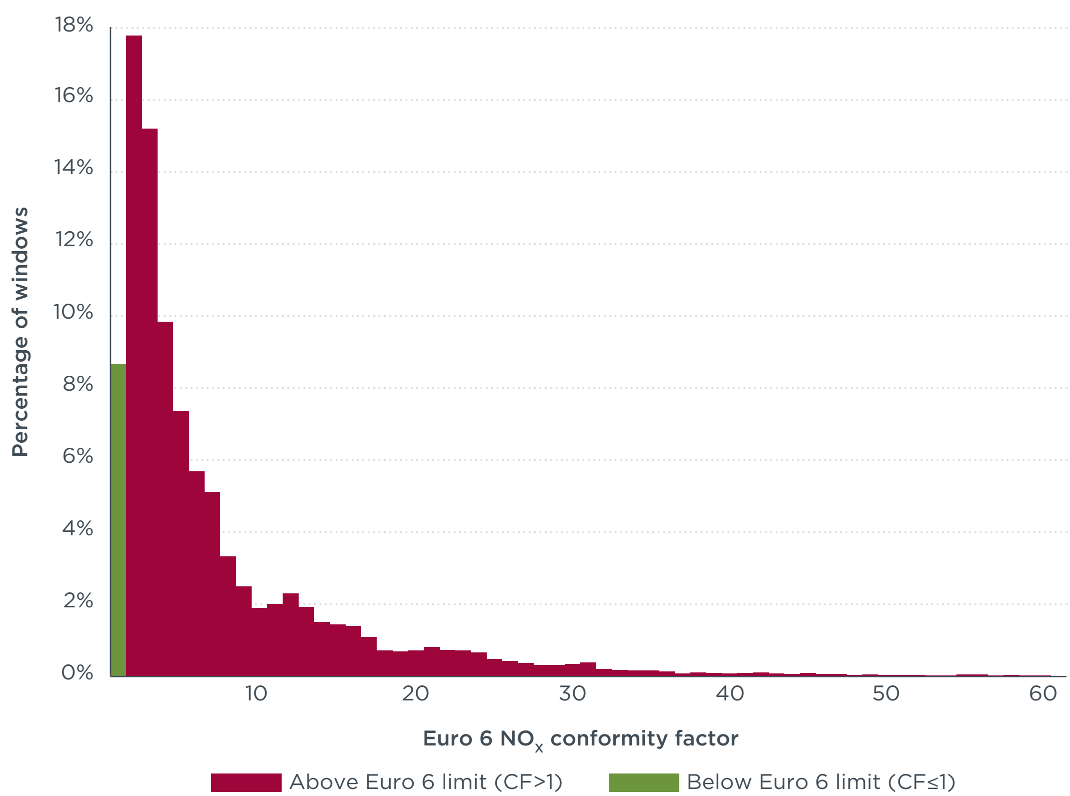

Figure 12: Histogram of NO_x CFs (all windows)

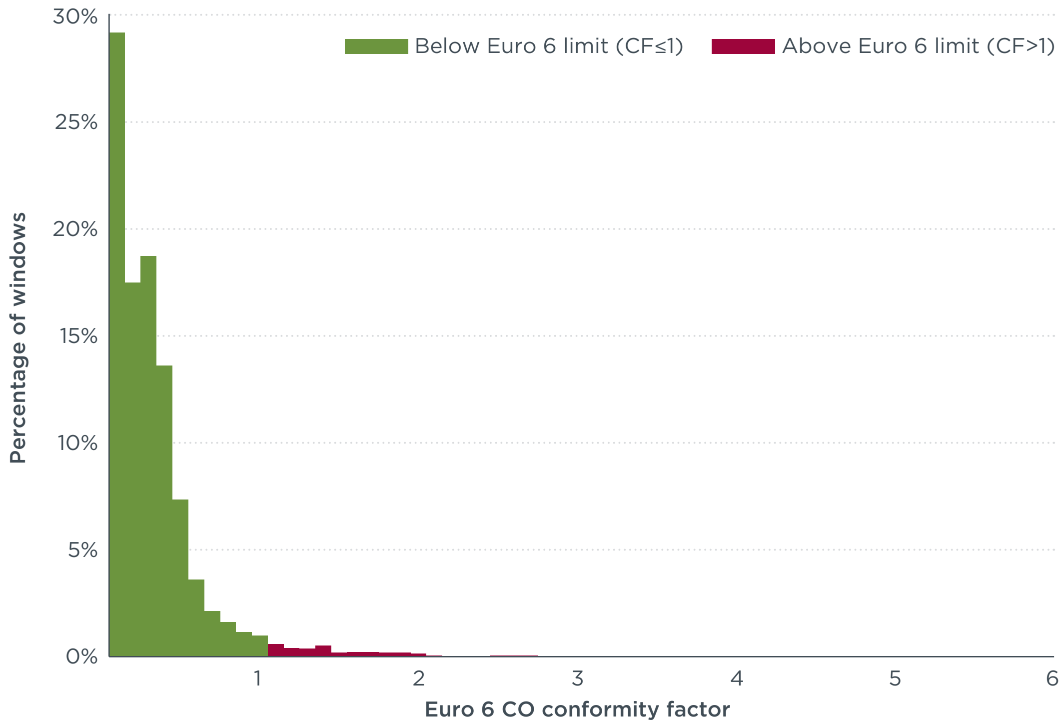

Figure 13: Histogram of CO CFs (all windows)

In Figure 14, we plot the histogram of on-road to type-approval CO_2 ratios for all windows. This resulted in an average windowed CO_2 emission of 143% of the type-approval value, which is consistent with the gap between the real fuel economy experienced by drivers and the figures derived from type-approval values estimated by Mock et al. (2013).

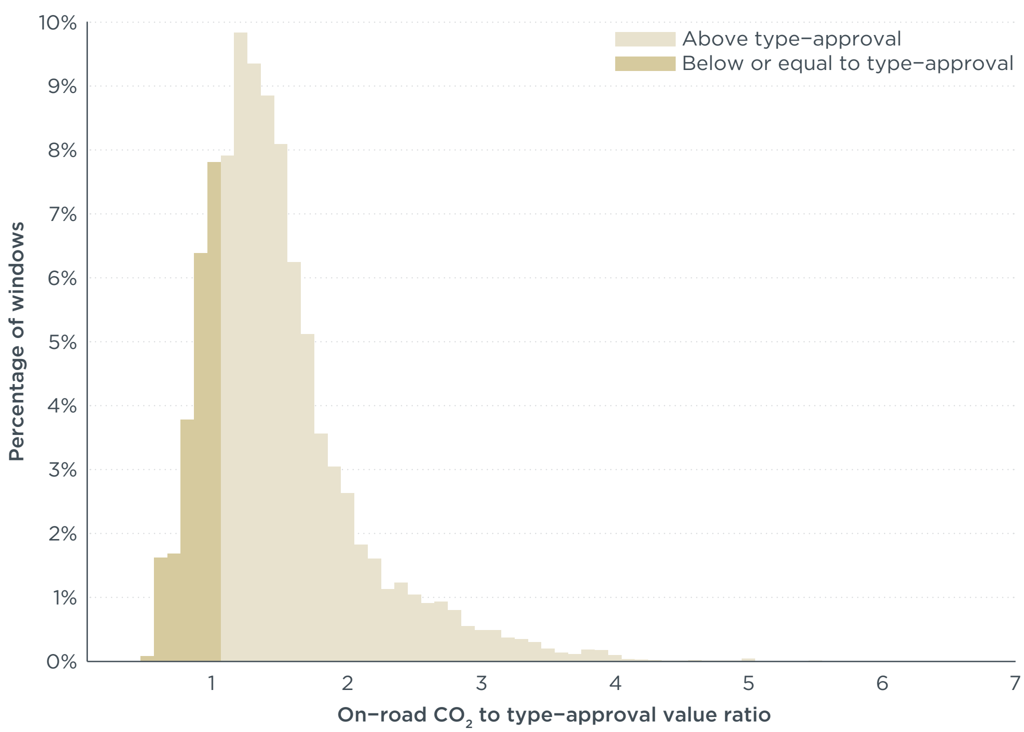

Figure 14: Histogram of on-road to type-approval CO_2 ratios (all windows)

In order to investigate the relationship among CO_2, NO_x and CO, the corresponding conformity factors (CFs) and on-road CO_2 ratios of the windows are plotted in pairs as scatter plots in Figures 15 to 17. These plots give additional information about the magnitude and the nature of the NO_x problem that was not apparent from Figures 12 to 14, because they show how the emissions of NO_x, CO, and CO_2 are related.

First of all, in Figure 15 (where the CFs for NO_x for all windows are plotted against the corresponding CFs for CO) it is possible to observe a tradeoff between CO and NO_x emissions (when the CF for NO_x is high, the corresponding CF for CO is usually low). On the other hand, the observed CFs reach much higher values for NO_x, which points at insufficiently controlled NO_x emissions during real-world driving.

In Figure 16, the windowed CFs for NO_x are plotted against the ratio of windowed distance-specific CO_2 emissions to the (vehicle-specific) type-approval value. In this chart, it is possible to observe a clear trend whereby the highest CFs for NO_x tend to occur when the distance-specific emissions of CO_2 are highest. Also, it is instructive to observe the large scatter in NO_x CFs at the higher ratio of CO_2 emissions. For some windows, NO_x emissions stayed low even at high loads, while others had NO_x emissions orders of magnitude higher.

In Figure 17, the windowed CFs for CO are plotted against the ratio of windowed distance-specific CO_2 emissions. In this case, the relation between high CO CFs and high on-road CO_2 ratios is less apparent.

Figure 15: Scatterplot of CO and NO_x conformity factors (all windows)

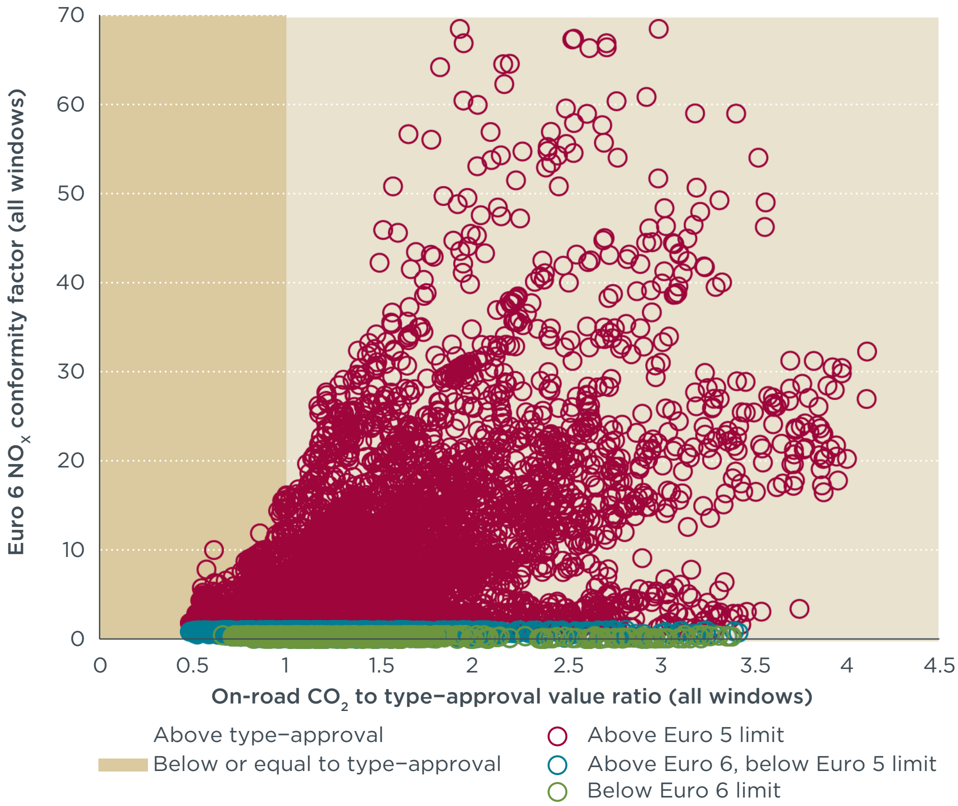

Figure 16: Scatterplot of NO_x conformity factors and on-road CO_2 ratios (all windows)

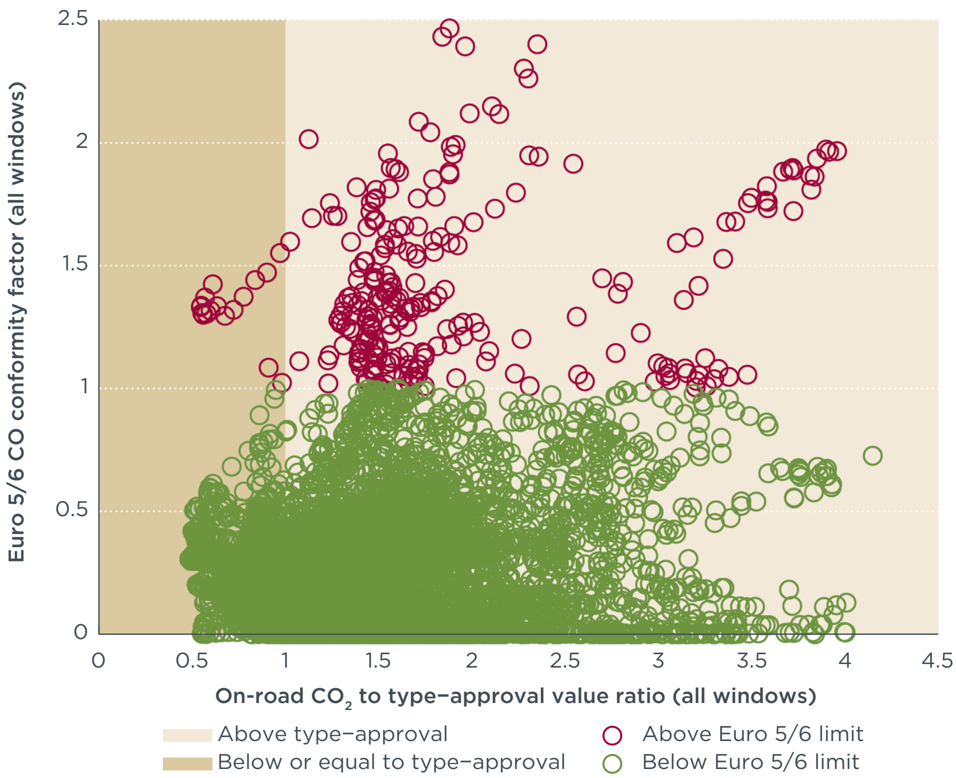

Figure 17: Scatterplot of CO conformity factors and on-road CO_2 ratios (all windows)

5.1.4.1 RESULTS BY VEHICLE

The results presented in Section 5.1.4.1 refer to all the CO_2 windows that could be derived from the experimental data (i.e., covering 15 different vehicles). It should be noted that each vehicle was driven for different distances and amounts of time. Therefore, the average conformity factors reported in the previous section are weighted according to the relative distribution of windows (Figure 18) and to the specific driving situations reported in Part 2 of this report. However, it is also possible to calculate the results for individual vehicles. This is done in Figures 19 to 21, which contain the histograms of the windowed conformity factors for NO_x and CO, and the histograms for the ratios of windowed distance-specific CO_2 to type-approval values.

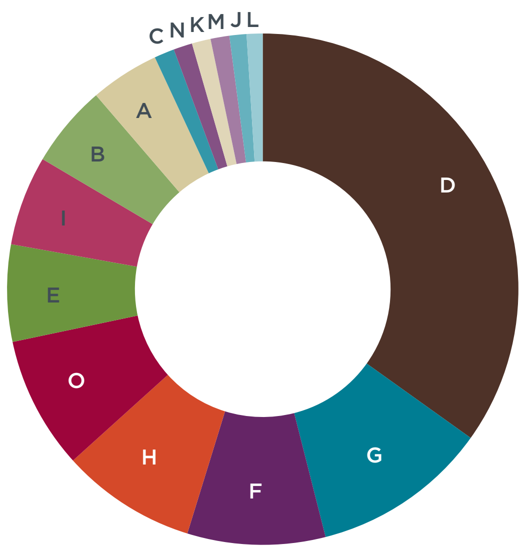

Figure 18: Shares of individual vehicles in the total number of CO_2 windows

Looking at Figure 19, we see that the on-road CO performance was very good across the board, with several vehicles staying in compliance with the Euro 5/6 limit for 100% of the windows. The worst performer was arguably Vehicle M (an SCR-equipped minivan for which 40% of the windows were outside of compliance), but even this vehicle was able to maintain an average conformity factor below 1 (0.9).

On the other hand, if we look at Figure 20, the compliance situation for NO_x is notably different. In this case, we have five vehicles with 0% of windows complying with the Euro 6 limit of 80 mg/km, plus five vehicles with fewer than 3% of windows in compliance, and three others with fewer than 15% of windows below the Euro 6 limit. Only two vehicles, B and C, had large shares of windows in compliance (roughly 50% each), and both used SCR systems. Looking back at Figure 18, we can see that most of the windows in compliance with Euro 6 for NO_x come from Vehicle D (with SCR NO_x aftertreatment), which had the most trips and the most windows of any vehicle in our measurement campaigns. This vehicle was a pre-series vehicle provided by the manufacturer, and it seems to exhibit a better NO_x behavior than the other three vehicles of the same make and model denomination (Vehicles E, F and G; also equipped with an SCR). The worst performers were Vehicles L and H (with average Euro 6 NO_x conformity factors of 25.4 and 24.3, respectively). Incidentally, Vehicle H was the only test vehicle equipped with an LNT, and it had the second-highest average conformity factor. The four vehicles without NO_x aftertreatment (I, J, K and O) all had NO_x conformity factors between 4 and 6, roughly in the middle of all the vehicles.

Another characteristic of the NO_x emission profile of the vehicles under test is a significant deviation between the mean and the median conformity factor observed for some vehicles. This is because the distribution of the NO_x conformity factors was skewed by the presence of a few windows with very high conformity factors (i.e., with very poor control of the NO_x emissions), which push the value of the average conformity factor upward.

In Figure 21, we see the histograms of the ratios of windowed distance-specific CO_2 to type-approval values. From these histograms, it is apparent that most test vehicles had on-road CO_2 emission values that were consistently above their corresponding type-approval value. It is worth noting that two of the vehicles with the lowest NO_X CFs—Vehicles B and C—had roughly average real-world CO_2 ratios, which suggests that low loads did not contribute to their good NO_X performance.

Figure 19: Histograms of windowed CO conformity factors, by vehicle

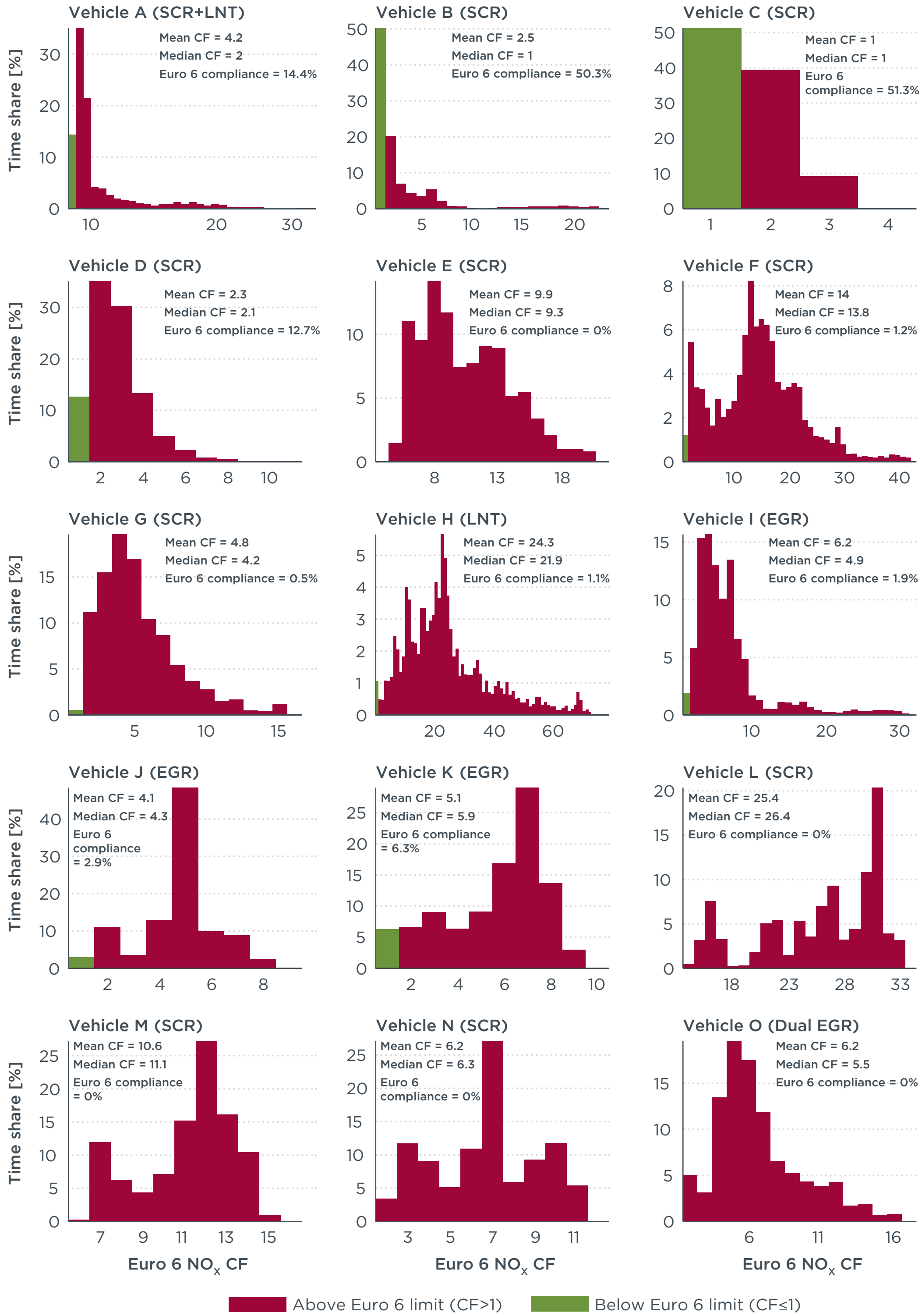

Figure 20: Histograms of windowed NO_x conformity factors, by vehicle

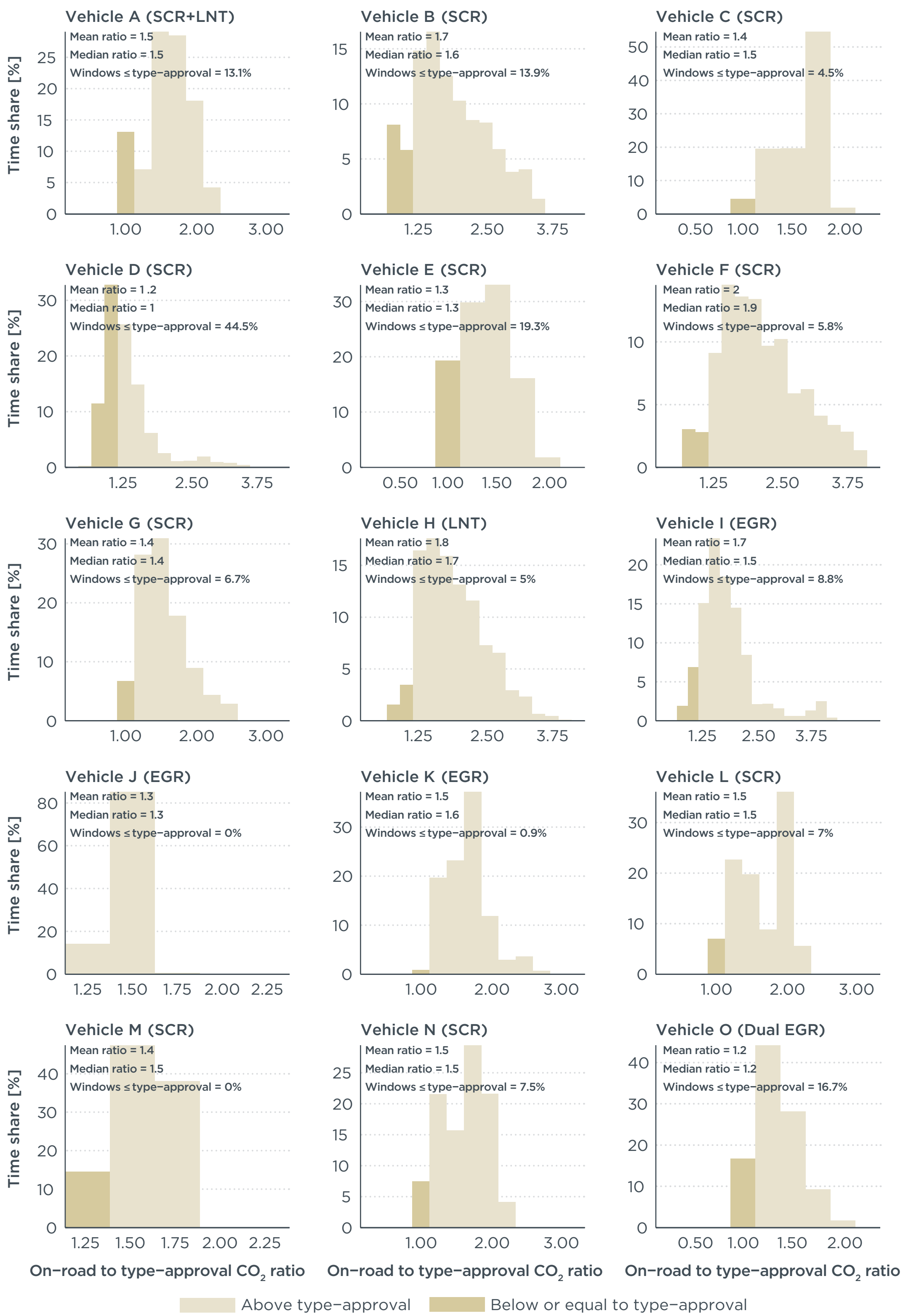

Figure 21: Histograms of windowed real-world CO_2 ratios, by vehicle

5.2 DISCUSSION

The main contribution of our meta-analysis is twofold. First, we gathered what, to our knowledge, is the largest collection of on-road tests of its kind presented to date. Second, we devised a consistent framework for the analysis and reporting of PEMS data that helps visualize the results of on-road testing and makes the most of the possibilities that PEMS testing offers to investigate the influence of real-world factors upon vehicle emission levels. We believe that PEMS will continue to gain relevance for both scientific and regulatory applications, and so we will continue to develop this analysis and reporting framework for future ICCT publications.

With this report, we have provided a substantial amount of experimental results to help characterize the real-world emission profile of CO_2, CO, NO_X, and THC for modern diesel passenger cars.[15] In particular, our aim was to gauge the extent of the problem of real-world NO_X emissions from these vehicles (see Section 2.1). Before the release of this meta-analysis, a handful of studies had presented useful but fragmentary evidence that the actual, on-road emissions of modern diesel passenger cars (Euro 6 in Europe and Tier 2 Bin 5/ULEV II in the US) were not sufficiently controlled for certain operating conditions that are part of normal driving. The breadth of the experimental basis for our meta-analysis provides a sound characterization of the on-road behavior of Euro 6 and Tier 2 Bin 5/ULEV II passenger cars. The results presented in this report can also help estimate the magnitude of the non-compliance problem with NO_X—which was well known, but not sufficiently quantified—and investigate potential causes of the elevated emission rates through a detailed inspection of the individual PEMS trips.

5.2.1 PEMS, Euro 6 and the future of passenger car emissions regulations

PEMS equipment has come a long way in terms of accuracy and ease of use since the first units for scientific applications surfaced in the 1990s. Current PEMS setups are sold as tightly integrated packages that provide reliable measurements of on-road emission rates of CO_2, CO, NO_X, and THC, plus exhaust flow and temperature measurements, GPS and weather information, and a data link to the ECU of the vehicle under test. Portable particle mass analyzers have recently become commercially available after extensive testing (Mamakos et al., 2011), and portable particle number (PN) analyzers are expected to be widely available by the time that the on-road measurement of PN becomes mandatory for the type-approval of Euro 6c vehicles in 2017.[16]

The main limitations of PEMS include the reduced range of measurable pollutants compared with a chassis dynamometer laboratory, the added mass (of approximately 50–75 kg for simple setup, and of up to 150 kg with additional instrumentation) that may bias the measurement, and the reduced repeatability due to real-world sources of variability. In our view, *these limitations are far outweighed by the ability to assess the influence of real-world driving upon emissions*. PEMS measurements arguably provide a better approximation of actual, on-road emission rates of regulated pollutants than any chassis dynamometer cycle—especially the type-approval cycles, because regulations based on chassis dynamometer testing create a strong incentive for manufacturers to optimize emissions behavior within the narrow boundary conditions of the certification test.

15 The EU-market vehicles covered were type-approved to the Euro 6 standard, and the US-market vehicles were certified to the US Tier 2 Bin 5/California ULEV II standard.

16 West Virginia University gathered particulate number information as part of the ICCT study of US diesel vehicles. Results can be found in Thompson et al., 2014.

In this sense, we are pleased to see PEMS gaining traction for regulatory use, and our colleagues in Europe—as demonstrated by this report—will continue to be involved in the activities of the European Commission's Real Driving Emissions from Light Duty Vehicles (RDE-LDV) working group in charge of amending the Euro 6 regulations to include PEMS testing as a part of the mandatory passenger car type-approval process. When the work of the RDE-LDV comes to fruition, Europe will be the first region of the world to use PEMS for the type-approval of passenger cars. All of the aspects of the regulatory PEMS test, from the technical requirements of the equipment and the setup procedure to the actual performance of the on-road tests and the post-processing of the measured signals, will be defined in a regulatory text that could substantially change the regulatory landscape for the emissions of passenger cars in Europe and set a precedent for other regions. We also expect PEMS equipment to be further refined and easier to operate to the point that it becomes one of the main sources of vehicle emissions data for the scientific and regulatory community, not just in Europe but in other regions as well.

5.2.2 Raw average emission factors

The raw average results of a single PEMS trip, or of a handful of trips performed with the same equipment, would hardly be sufficient to characterize the on-road emissions behavior of a single vehicle, let alone of a whole technology class of vehicles. It is easy to disregard some unusually high emission results from a single trip by attributing them to a malfunction in the equipment, improper calibration, errors in the data handling, or unrepresentative driving conditions. But when—as we have done for this report—data for a large number of PEMS tests are collected from reputable sources and analyzed in a consistent manner, and when a similar emission behavior is repeatedly observed for a sufficiently large number of vehicles, valid conclusions can be made about the general on-road behavior of the vehicles under test.

What we observed for the PEMS trips covered in our analysis is that, even though the raw average emission factors for CO and THC stayed comfortably below the Euro 6 limit during the on-road tests, *the measured NO_x emission rates of the large majority of the vehicles under test were unsatisfactory*. The otherwise excellent results for CO and THC were overshadowed by a generalized extremely poor NO_x performance that confirms the results of previous studies and points to insufficiently robust emission control strategies. For this reason, we will focus the rest of the discussion on NO_x.

The poor NO_x emissions behavior was observed for vehicles equipped with in-cylinder NO_x control, LNT, and SCR technology. Incidentally, one of the worst performers on average was the only vehicle equipped with LNT—Vehicle H, a Tier 2 Bin 5/ULEV II vehicle tested by West Virginia University for the ICCT. Despite this, it would be unwise to suggest that LNT does not deliver acceptable on-road performance, due to the lack of additional on-road measurements from other vehicles equipped with this technology. On the other hand, this vehicle exhibited good NO_x performance during additional chassis dynamometer tests under the US FTP and EU NEDC cycles (see Thompson et al., 2014), which points to an aftertreatment system management strategy optimized for the certification cycle rather than for real-world driving.

Another particularly bad performer was a vehicle equipped with SCR technology (Vehicle L, for which only one trip with relatively mild driving conditions was available). On the other hand, the two (relatively) cleaner vehicles (Vehicles B and C) were both equipped with SCR. The four vehicles with in-cylinder NO_x control (I, J, K and O) had similar performance, and were average relative to all vehicles tested (i.e., unsatisfactory in absolute terms).

5.2.3 Situation-specific emission factors and windowed analysis

It could be argued that the high raw NO_x emission factors were skewed due to the design characteristics of the test routes (e.g., a disproportionate share of uphill or urban driving after a cold start), by an aggressive driving style from the test drivers, or by extreme environmental conditions (e.g., freezing weather). The detailed results of our meta-analysis provide sound arguments to dispel these objections. For example, one can refer to the characterization of the PEMS trips in Section 5.1.2, which shows a balanced distribution of velocity, gradient and acceleration shares for the vast majority of the trips. Also, upon inspection of the situation-specific NO_x emission factors presented in the tables of Section 5.1.3, it is apparent that high emissions of NO_x occurred not just during the real-world driving situations where the engine/aftertreatment would be the most challenged, but also during undemanding conditions after the artificial exclusion of high acceleration*velocity, uphill driving, and cold temperature (see the definitions of “Undemanding 1” and “Undemanding 2” in Table 3, and their corresponding trip emission factors in Table 7). Furthermore, the detailed assessment of individual trips presented in Part 2 of this report can be used to assess the environmental and driving conditions for all of the PEMS trips, as well as to inspect the causes that lead to elevated emissions in some situations.

The CO_2 window analysis provides further confirmation that the NO_x issue is present even during moderate, low-load driving situations. This is observable in Figure 22. This chart plots the mean and the median NO_x conformity factor (i.e., the ratio of calculated distance-specific NO_x emissions for the window to the Euro 6 limit) for all windows with a real-world CO_2 ratio (i.e., the ratio of calculated distance-specific CO_2 emissions for the window to the type-approval value) lower than the cutoff point X. What this chart shows is that, even for a conservative cutoff point of 1.4 (i.e., with the exclusion of all CO_2 windows with distance-specific CO_2 above 140% of the type-approval value[17]), the median conformity factor for NO_x for all 15 vehicles lies above 3 (“Very conservative CF estimate” in Figure 22).[18] And this is in spite of the fact that most of the CO_2 windows correspond to the relatively clean, pre-series Vehicle D (see Figure 18).

17 This is approximately the most frequent value for the real-world CO_2 to type-approval value ratio (see Figure 13).

18 Because of the skewed distribution of the CFs (i.e., the presence of extreme high values), the median is a more conservative estimator than the mean, which in this case would lie around 5.5 (“Conservative CF estimate” in Figure 22) for all windows below a cutoff point of 140% of the type-approval CO_2 value.

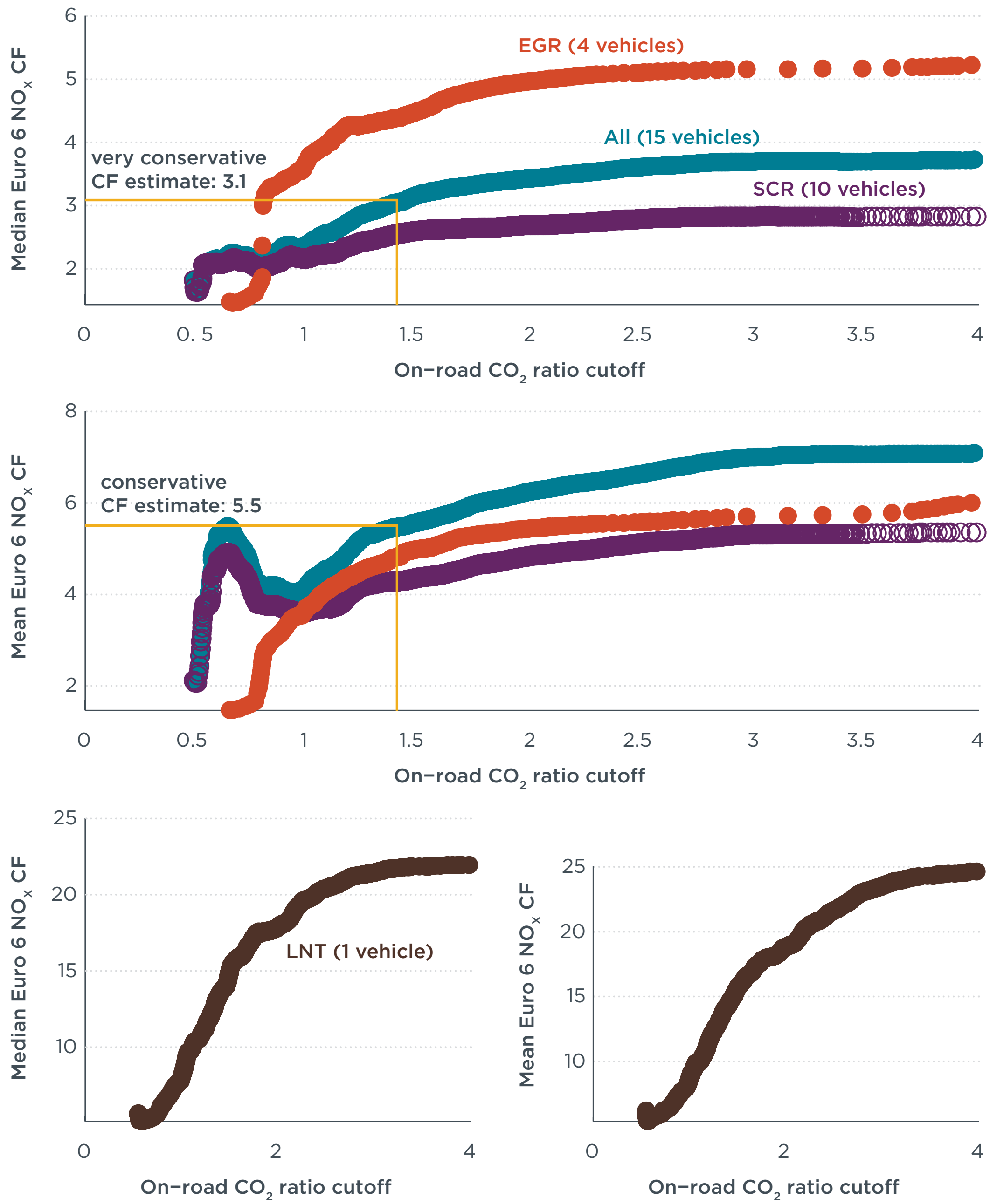

Figure 22: Mean and median Euro 6 NO_x CF as a function of CO_2 ratio cutoff point (by NO_x control technology)

5.2.4 Real-driving emissions and (real) clean diesel cars

All of the passenger cars analyzed in this report were certified to stringent emissions limits (below 80 mg/km over the NEDC cycle for the Euro 6 vehicles, and below 50 mg/mi [31 mg/km] over the FTP cycle for the Tier 2 Bin 5/ULEV II vehicles). So why was the on-road performance so markedly worse in most cases? First of all, we must consider that these low emission values were attained during type-approval tests, i.e., during a reduced number of tests performed on a few vehicles within a defined set of boundary conditions and following a predetermined chassis dynamometer laboratory test procedure. It is well known that type-approval test cycles (especially the NEDC) represent milder driving conditions than those occurring in the real world. Real-world driving includes uphill driving, brisk accelerations, cold weather, use of HVAC and other auxiliaries, and so on. These factors are not entirely covered by type-approval procedures. Hence, due to a pure increase of energy demand on the engine, real-world driving will lead to average fuel consumption (and also CO_2) values above the official, laboratory figures (see Mock et al., 2013).

This increase in fuel consumption and CO_2 emission values (which on average amounted to approximately 40% of the type-approved values for our test vehicles; see Figure 14) would be an expected outcome of on-road tests, and even an acceptable one in the short term (although it points towards the need for improvements in the type-approval procedures to make them more realistic). Following this logic, it could be acceptable to have a proportional, average increase of 40% in the emissions of other pollutants. In other words, if the CO_2-normalized emission values of the other pollutants stayed within the legal emission limits, we could say that we have a vehicle that is clean under real-world driving. The vehicles under test were "real-world clean" by that measure for both CO and THC, sometimes by a comfortable margin even. But unfortunately this was not the case for NO_x.

So what makes NO_x different? A possible reason behind the real-world diesel NO_x issue is that this is not an easy pollutant to control. For example, the proper *urea dosage in SCR systems* is difficult to calibrate, as an excessive amount of urea injection in the exhaust stream can lead to high ammonia emissions at the exhaust tip ("ammonia slip"). It is also more difficult to inject the proper dosing during rapid throttle variation, which would explain the high emissions during transient accelerations. Manufacturers also have an incentive to err on the side of too little urea injection, as this both reduces the chance of ammonia slip and extends the urea refill intervals (which could inconvenience drivers of diesel cars if they became too frequent). On the other hand, LNT systems have a fixed NO_x capacity, and momentary high-load situations can create NO_x breakthrough.

Another possible explanation for the high NO_x emissions from diesels is that robust control of NO_x emissions is likely to result in a small fuel penalty that—unlike high on-road NO_x emissions—can be directly perceived by the users of the vehicles and negatively affects compliance with the CO_2 standards, thereby creating an incentive for manufacturers to optimize fuel consumption to the detriment of NO_x performance.

In spite of the discouraging results presented in this report, we believe that real-world clean diesel cars are possible, and that the technologies to achieve this are already in the cars being sold in the market. We find reasons to be (moderately) optimistic in the behavior of Vehicle B. This vehicle was extensively tested and it behaved acceptably, despite facing some of the most demanding acceleration*velocity and road grade situations of all vehicles tested.

We are also hopeful because manufacturers have more than one technology option to choose from, some of which can be applied in combination. These aftertreatment technologies are being installed in today's diesel vehicles, and they could conceivably be tweaked to deliver good real-world NO_x performance (on par with the rest of the regulated pollutants) without increasing the retail price of the vehicles (e.g., SCR-equipped diesels could adjust their urea dosing strategy and equip larger tanks to avoid inconveniently short refilling intervals). Finally, it is our hope that our input to the discussions of the RDE-LDV will help design a regulation that sets the right incentives for the robust application of diesel emission control technologies, and that ensures that diesel passenger cars remain an attractive option to customers in the EU and US.

6 CONCLUSIONS AND RECOMMENDATIONS

In this report we have presented our PEMS meta-analysis of modern diesel passenger cars, for which we assembled a large dataset of measured on-road emissions and applied a consistent framework for the analysis and reporting of the results. Thanks to the generous contribution of third parties, which is gratefully acknowledged, the broad experimental basis of our assessment gives us a good level of confidence in the results and encourages us to share our thoughts with the regulatory and scientific community.

The average on-road emissions of CO and THC remained consistently low for all the vehicles under test. This otherwise praiseworthy behavior was overshadowed by a generalized unsatisfactory emission profile of NO_x. High NO_x emissions were observed across vehicles, regions (US and EU), manufacturers, and aftertreatment technologies. They were heavily present not just in the more demanding driving situations (e.g., uphill driving, instances of high acceleration*velocity), but also during the situations that would in principle be most favorable to achieve low NO_x emissions. This points to the application of NO_x control strategies that are optimized for the current type-approval test procedures (on the chassis dynamometer laboratory, using a standard test cycle), but are not robust enough to yield acceptable on-road performance. This engineering approach, albeit legal in the current regulatory context, entails a risk for manufacturers that are heavily invested in diesel technology, because it can steer environmentally conscious customers away from their offerings. Ultimately, it is also unlikely to be sustainable after PEMS testing is introduced for the type-approval of passenger cars in the EU in 2017.

The vehicles covered in our meta-analysis have only recently been introduced to their corresponding markets. The current share of Euro 6 Diesel vehicles in the European fleet (and of Tier 2 Bin 5 Diesel passenger cars in the US) is thus rather small. *But unless sound regulatory action is taken, the gradual introduction of these vehicles into the fleets will have a disproportionate negative impact upon air quality, especially in Europe where the popularity of diesel cars remains high*. In this sense, the results of our meta-analysis are especially relevant to the work of the RDE-LDV working group in charge of amending Euro 6 regulations to include PEMS testing as part of the type-approval process of passenger cars in Europe. Until this amendment is enforced in 2017, there will be no legal requirement for vehicle manufacturers to achieve low real-world emissions of NO_x, and the issue that we identified in this report will remain an open gap in the European vehicle emissions regulations.

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