LENS L-vehicles Emissions and Noise mitigation Solutions

D4.4
Suggested revisions to exhaust emissions TA procedure

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Disclaimer

Revisions table

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Executive summary

This report serves as a base for recommendations for modified / adapted type approval regulations regarding exhaust emission. In the course of the LENS project, exhaust emission measurements of 150 L-category vehicles were conducted. Laboratory test according type approval regulations and with real world cycles as well as measurements on-road with on-board measurement equipment delivered insights on the exhaust emissions performance of different L-category vehicle types. The tests were distinguished into WMTC (current type approval test), RDC (real world drive cycle in laboratory) and RDE (Real World Test on-road). For suggested revisions to exhaust emission type approval procedure, measurement results of EURO 5 and EURO 5+ L-category vehicles were separately analysed.

Finding 1: The fleet emission of L-category vehicles is considerably higher in real world driving than what measured under type-approval conditions in the laboratory.

- The data showed that—for most sub-categories—the average emission level is below the current limits set on the basis of the WMTC test procedure. Only the small mopeds category (L1-b) and Enduro motorcycles (L3e-AxE) show considerable higher CO and HC values, whereas small Quads (L6e-B) show higher NOx emission.
- Over the more realistic driving pattern RDC conducted in the lab, almost all sub-categories exceeded both the CO and the NOx limit, and the small L1e-B vehicles considerably also exceeded the HC limit[1].
- When tested on the road with portable devices, CO and NOx emission of the majority of sub-categories are found considerably higher than the Euro 5 limit[1].

Finding 2: In EURO 5 vehicles, non-regulated pollutants, including particle number (PN), particulate mass[2] (PM) and ammonia (NH_3) exhibited high levels. In several cases, PM and PN were found above the limit of the current passenger car regulation. CO_2 emission increase with engine capacity and power and tend to increase from WMTC to RDE and RDE.

- For the WMTC test all 2- and 3-wheeler show low levels of NH3, whereas some of the vehicles of the Quad sub-category have high to very high levels of NH_3 emission. In the more realistic RDC and RDE tests the bigger motorcycles exceed the passenger car EURO 7 limit.
- PN emissions with a cut-off diameter of 10nm are in many cases in all classes and in all tests around the passenger car EURO 6 limit, but in some cases exceeding by far the passenger car EURO 6 limit.
- PM emissions exceed in several cases the EURO 6 passenger car limit.

Finding 3: Standardized and commercially available measurement equipment for on-road tests is suitable for vehicles with lager dimensions, weight, and power like L3e-A3 or Quads only. Installation of the portable measurement systems is more demanding for L-category vehicles than for passenger cars and the necessary monitoring of the driving parameters during the test is difficult for L-category vehicles. Smaller vehicles like mopeds or small motorcycles can be equipped with miniaturized systems measuring several emission components, currently available in prototype status only.

[1] It has to be noted that no phase weighting has been applied to these measurements.
[2] Regulated only for CI and PI Direct Injection engines

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Out of these findings the following recommendations for type approval procedure modifications are given:

Recommendation 1: Major differences between the type approval test (WMTC) and real-world tests in the lab (RDC) and on the-road (RDE) are the wider engine operation area and more dynamic driving behaviour in real-world over WMTC. Therefore, introducing a more realistic operation in type-approval is recommended. This can be done either by introducing a full on-road RDE test, or a real-world driving pattern in the lab. In the latter, more realistic running resistances should be introduced. Any of these actions requires further development for determining the exact specifications of the proposed changes.

Recommendation 2: Several—currently non-regulated pollutants show high levels, in some cases far exceeding the established limits of passenger cars. In particular, particulate mass (PM) and particle number (PN), but also ammonia (NH_3), exhibit disproportionately high levels but also other emission components should be better controlled. It is therefore recommended to include these components in the type approval procedure.

Recommendation 3: CO_2 emissions are in some cases considerably high and in the range with much heavier passenger cars. Today, only CO_2 reporting is required for L-category vehicles. To control CO_2 emissions, it is therefore recommended that CO_2 emissions are also put in focus.

Recommendation 4: Further research and development are required to miniaturize the on-board measurement equipment (PEMS) for regulated emission components to make it suitable also for the small L-category vehicles. Measurement technology on-board (FTIR) for non-regulated gaseous emission components is available in prototype status only; further research and development must be performed to enhance these instruments for type approval use.

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List of abbreviations

Abbreviation	Name
a_{pos}	Positive acceleration
ATV	All-terrain vehicles
CARB	California Air Resource Board
CI	Compression Ignition
CO	Carbon monoxide
CO2	Carbon dioxide
CVS	Constant Volume Sampler
CVT	Continuous Variable Transmission
DI	Direct injection
E10	Gasoline fuel with 10% Ethanol content
EPA	Environmental Protection Agency
EURO 5	EU emission regulation 5
FAME	Fatty Acid Methyl Ester
FTIR	Fourier Transform Infrared Spectroscopy
GTR	Global technical regulation
HC	Hydro Carbons
HDV	Heavy Duty Vehicles
KPI	Key performance index
LDV	Light Duty Vehicles
LENS	L-Vehicles
MC	Motorcycle
mFTIR	Mini Fourier-Transform-Infrared-Spectroscopy
Mini-PEMS	Miniaturized Portable Emission Measurement System
NH3	Ammonia
NMHC	Non-Methane Hydro-Carbons
NO	Nitric Oxide
NOx	Nitrogen Oxides
OEM	Original equipment manufacturer
PEMS	Portable Emissions Measurement System
PHEM	Passenger Car and Heavy-Duty Vehicle Emission Model by FVT / TU Graz
PI	Positive Ignition
PM	Particulate matter
PN	Particulate number
PWR	Power-to-weight ratio

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RDE	Real Driving Emissions
RPM	Revolutions per minute
RWC / RDC	Real World Cycle / Real Drive Cycle, a chassis dynamometer driving cycle representing real world driving
SEMS	Sensor-Based Emission Measurement Systems
SPN10 / PN10	Solid particle number with cut-off diameter 10nm
SPN23	Solid particle number with cut-off diameter 23nm
TA	Type Approval
TWC	Three-way catalyst
v	velocity
v_{max}	maximum design speed
WLTC	Worldwide harmonized light vehicles test cycle
WMTC	Worldwirde harmonized motorcycle test cycle

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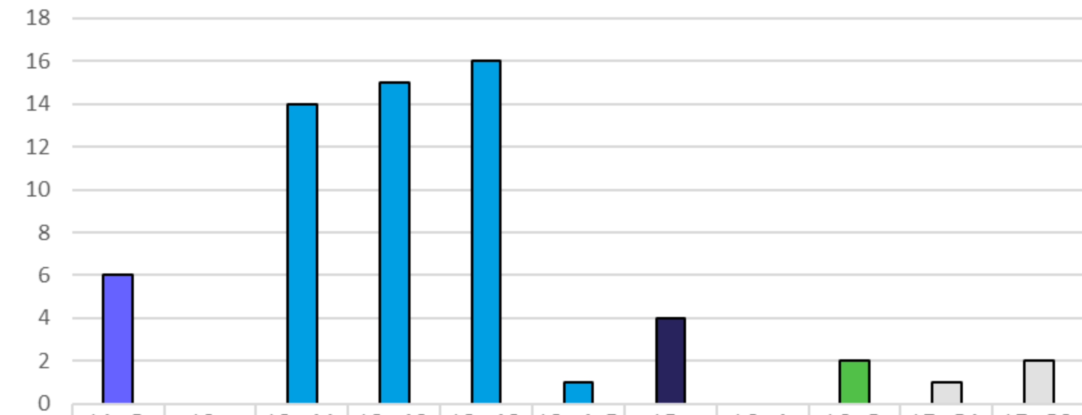
1 Introduction

Within the project LENS a measurement campaign with 150 vehicles for exhaust emission and noise was conducted. One output, based on the findings from this measurement campaign, is to give recommendations for improvement of the type approval procedures to ensure a reduction of the exhaust gas and noise emission. This means the detection of weaknesses of the current type approval method, the evaluation of possibilities to perform real drive emission testing within the type approval test procedure and the assessment of the suitability and readiness of measurement instruments for emission testing. This report focusses on exhaust gas emission and the outcome of these tasks with suggested revisions to exhaust emission TA procedures, in particular the type approval procedure test type I [1]. As the recommendations are based on results and findings, presented in other LENS deliverable reports[3], and further analysis regarding the impact of the recommendations will be made, no final conclusion is given in this report. Instead, these conclusions will be given at a later stage in the final reports of LENS work package 6.

The measurements conducted, described in the Deliverable Report D3.4., serve as the basis for these recommendations. Although exhaust emission from L-Cat vehicles type approved in several emission classes have been measured, for the recommendations of type approval modifications and improvements in this report only L-Cat vehicles in the latest emission class EURO 5 and EURO 5 plus are considered. In the following the conducted measurements are described in short for reference in this report.

1.1 Overview of conducted measurements and gained data

150 vehicles were tested for exhaust emissions in total [4], all of them in use with a minimum mileage of 500 km. The 61 vehicles considered for this report are type approved according to EURO 5 and EURO 5+ plus two additional vehicles belonging to the T-category (tractors). In Figure 1 the distribution of the L-cat vehicles EURO 5 / EURO 5+ are shown. The majority belongs to the L3 as well as the L1 category, which reflects the approximate market share.



	L1e-B	L2e	L3e-A1	L3e-A2	L3e-A3	L3e-AxE	L5e	L6e-A	L6e-B	L7e-B1	L7e-B2
Euro5	6	0	14	15	16	1	4	0	2	1	2

Figure 1: The number of L-category vehicles measured in the measurement campaign by subcategory with type approval EURO 5 and EURO 5+.

[3] https://www.lens-horizoneurope.eu/
[4] Deliverable D3.4

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The two additional vehicles of the T-category were measured, because L7e-B vehicles (heavy all-train quad and side-by-side buggy) are in most cases type approved as T category and not in the L-category. Reasons are the less stricter emission regulation and the higher possible power.

1.1.1 Type of emission measurements

The measurements were performed in laboratory according to the EURO 5 type approval procedure using the WMTC driving cycle, consequently designated as WMTC measurements and WMTC measurement results. Additionally, measurements in lab using and so-called real driving cycle RDC were conducted. The RDC was recorded with the same vehicle category using GPS track data (speed, time, inclination) and then driven on a chassis dynamometer. This measurement is called RDC. Finally, emission and driving data were recorded during on-road measurement trips on public roads of urban, rural and highway character. The emission data was gathered using different types of mobile emission measurement systems like PEMS[5], SEMS[6] or mini-PEMS[7]. Results from RDE measurements are listed as RDE results. For information about the measurement equipment as well as the measurement procedure we refer to the LENS delivery reports D3.1 "Method and systems for on-board measurement of pollutants emission" and D4.1 "Procedure for measuring in-lab LV exhaust emission"

1.1.2 Analysis of high emission events

To assess the contribution of specific real-world motorcycle driving events to high pollutant emissions an analysis built on hypotheses from Deliverable D6.1 was performed. The full content of the analysis is contained in Deliverable D3.5. Nine driving events were identified to be potentially linked to elevated emissions. These events, summarized in Table 1, were initially selected based on their known association with high noise emissions. To ensure a focused and practical analysis, a prioritization of the nine driving events has been applied. Events that are relevant across all vehicle types and that persist for more than a few seconds are given higher priority. Consequently, events 2 (rpm burst), 4 (maximum rpm), 8 (rpm fluctuation), and 9 (backfire) are considered lower priority in this phase of the analysis due to their limited duration or specificity to certain vehicle types. Consequently, the analysis identifies and quantifies emissions from selected driving events within the LENS database, focusing on cold start, acceleration from standstill, and deceleration transitions due to their relevance in real-world motorcycle use.

[5] PEMS Portable Emission Measurement System
[6] Sensor-Based Emission Measurement Systems
[7] Miniaturized Portable Emission Measurement System

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Table 1: Overview of driving events (adapted from D6.1, table 4.2.)

Condition	Vehicle Operation	Already in Emission TA?
(1) Cold start (mainly for emissions)	Engine start	Yes
(2) Rpm burst (revving)	Stationary, short activation and release of accelerator	No
(3) Acceleration from standstill, G1, G2, loaded + unloaded	Acceleration, late gear change	Partly
(4) Max rpm: esp. mopeds, scooters, sports MCs	Constant speed with max rpm	No
(5) Transition from constant speed or acceleration phases to deceleration phases	Deceleration	Partly
(6) 'Max' acceleration from standstill, G1, G2	Acceleration	No
(7) (Heavy) acceleration at speed, from 50 to 100 km/h	Acceleration, may be varied	No
(8) Rpm fluctuation	Variable speed	No
(9) Backfire (occurrence, distance not critical)	Multiple gear changing or manual operation	No

Methodology

Measurements within the LENS database were selected based on the following filtering criteria:

- Only motorcycle measurements were included.
- Only data from Real Driving Emissions (RDE) or Real-world Cycle (RWC) / Real-Drive-Cycle (RDC) conditions were considered.
- NO_x signals were required to be present within the measurement data, with one exception using NO as a proxy.

A total of 58 measurements passed the filtering criteria. Emissions were calculated for identified events and compared to full-trip averages.

In parallel, an additional analysis has been carried out. Measurements from LENSdb were evaluated, encompassing both laboratory (RDC and WMTC) and RDE test cycles of Euro 5 vehicles. A total of 195 tests have been considered. For each test, instantaneous data were utilized. Pollutants considered are: HC, CO and NO_x. Emissions of these pollutants have been analysed against several KPIs to understand the root causes of high emissions, so then a better assessment of current TA regulation can be developed. KPIs selected are the following: v*a, engine speed (rpm), vehicles speed, engine load, coolant temperature, throttle position and air-fuel ratio, when available. Not all these ECU signals were available on all measurements. To ensure a more precise assessment of emissions during steady-state driving conditions, in the following section, cold start phases (first 50s) were intentionally excluded from the dataset, thereby providing a focused analysis of the dynamic conditions associated with elevated pollutant generation. Events with vehicle speed value lower than 5 km/h have been neglected in the process of converting g/s emissions into g/km.

To isolate the high emission events from that took place throughout the measurements, a second analysis was performed only with the instantaneous values that exceeded a determined threshold to isolate those high emission events. With this purpose, each consecutive value that exceeded the limits was grouped in blocks, as can be seen in green shading in Figure 2. Each block is considered a unique event and to characterize each of them, mean, maximum, and minimum values are calculated from the instantaneous values belonging to the group that have been calculated. Additionally, RPA and delta velocity were calculated to analyse how dynamics can have an effect on emissions.

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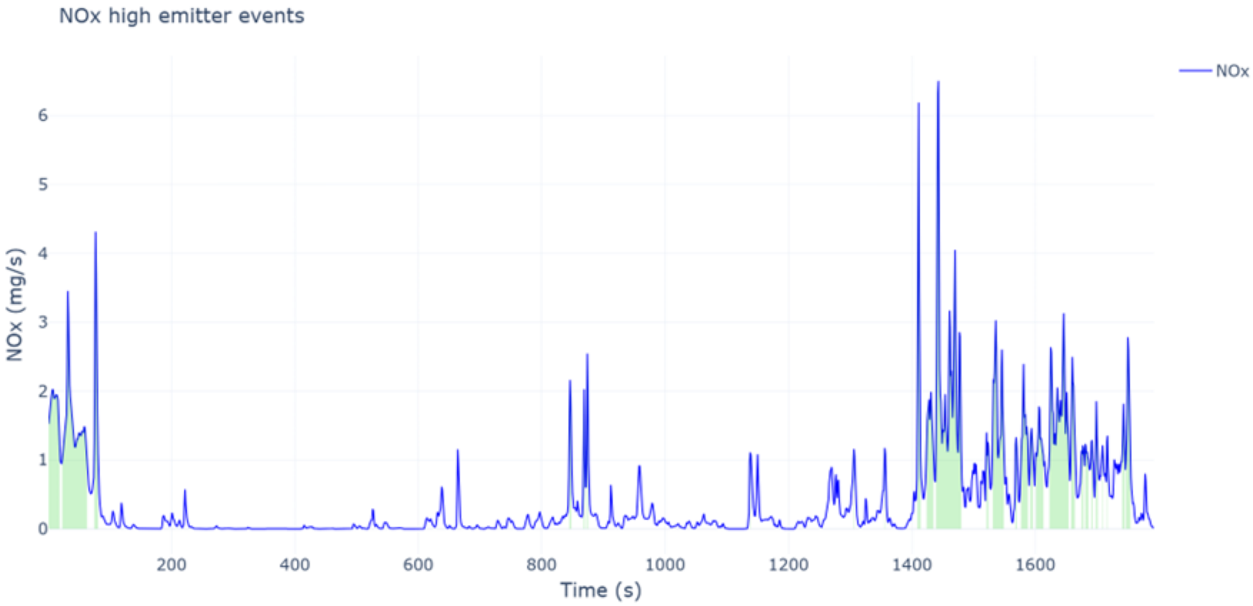

Figure 2: Identification of NOx high emitter events

1.1.3 Determination of real-world running resistance

Measuring L-category vehicles in a laboratory setting requires that the chassis dynamometer is set in such a way that the vehicle experiences the same running resistance as it would when driving on the road. For example, there is no wind speed in the laboratory, therefore the air drag is simulated by the chassis dynamometer. The procedure for determining the on-road running resistance and setting the chassis dynamometer accordingly is described in EU Regulation No 134/2014, and consists of two steps:

1. A coast-down test procedure to determine the on-road running resistances, referred to as the 'road-load', as specified in Appendix 7 of EU Regulation No 134/2014.
2. A procedure to set the chassis dynamometer to reproduce the road load, as specified in Appendix 3 of EU Regulation No 134/2014

As an alternative, Appendix 5 of EU Regulation No 134/2014 offers the possibility to apply standard values for setting the chassis dynamometer, which are based solely on the mass of the vehicle, so without the need for measuring the actual running resistance.

An analysis to determine the differences between real-world running resistances and the table values was performed to provide better comparison between results from on-road and lab tests (see chapter 7). For that purpose, road-load measurements were conducted on several motorcycles with manual gear shift[8]. These measurements and additional running resistance data were then analysed and compared to the table values of Appendix 5 [2].

[8] Vehicles with CVT powertrain or automatic transmission were not included in the analysis

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2 Summary and conclusions of exhaust emission related measurements

The exhaust emission related measurements from the campaign are described in detail in Deliverable 3.4. In chapter 2 an excerpt of the results and conclusions are given, structured in WMTC, RDC and RDE as well as different emission components. In the following the results concerning regulated gaseous emission are shown (chapter 2.1), and in the next chapter in EURO 5 non-regulated emission components are described (chapter 2.2). For both emission component categories observations are highlighted (chapter 2.3) and in chapter 2.4 the effect of high emission events is discussed. Additionally, analysis of real-world driving resistance (chapter 2.5) were performed. Finally, the observations are discussed and the findings explained in chapter 2.6.

2.1 Regulated gaseous emission

The following figures depict the average gaseous emission levels of a sub-group of the tested vehicles per category and type of test. The sub-group of vehicles selected are Euro 5 and Euro 5+ vehicles which are not tampered. For CO, HC and NO_x emissions the respective Euro emission limit[9] is also shown with a horizontal line. It has to be noted, that for the WMTC the single phases of the test cycle are weighted and then averaged according to the type approval regulation. This was not done for the RDC and RDE cycles, which has to be considered for the comparison between WMTC, RDC and RDE.

2.1.1 CO emissions

For most categories the type approval CO emission levels were within the EURO 5 limit, but much higher CO levels were found of L1eB and L3e-AxE vehicles. Real drive measurements on-road (RDE) and in lab (RDC) showed that CO emission levels were much higher than in type approval test, in several cases higher than the type approval limit.

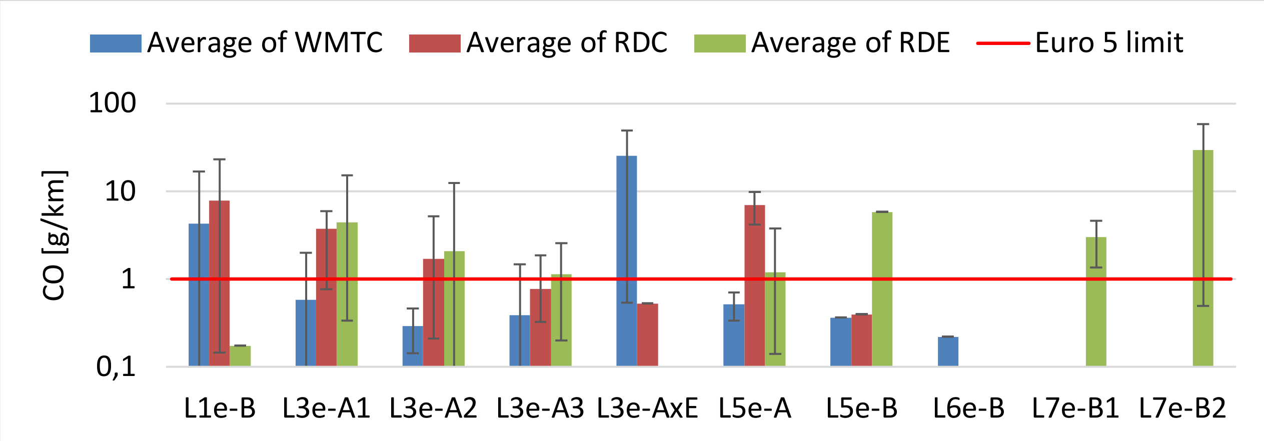

Figure 3: Average CO emissions per category and type of test including standard deviations.

[9] (1 g/km CO, 60 mg/km NOx, 100 mg/km HC)

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2.1.2 HC emissions

HC emissions could be measured only in lab condition as no portable HC measurement instrument could be used. In type approval tests, except for L1eB and L3e-AxE, which had very high HC emissions, the average HC emission level of the rest of the vehicle categories were within the EU5 limit.

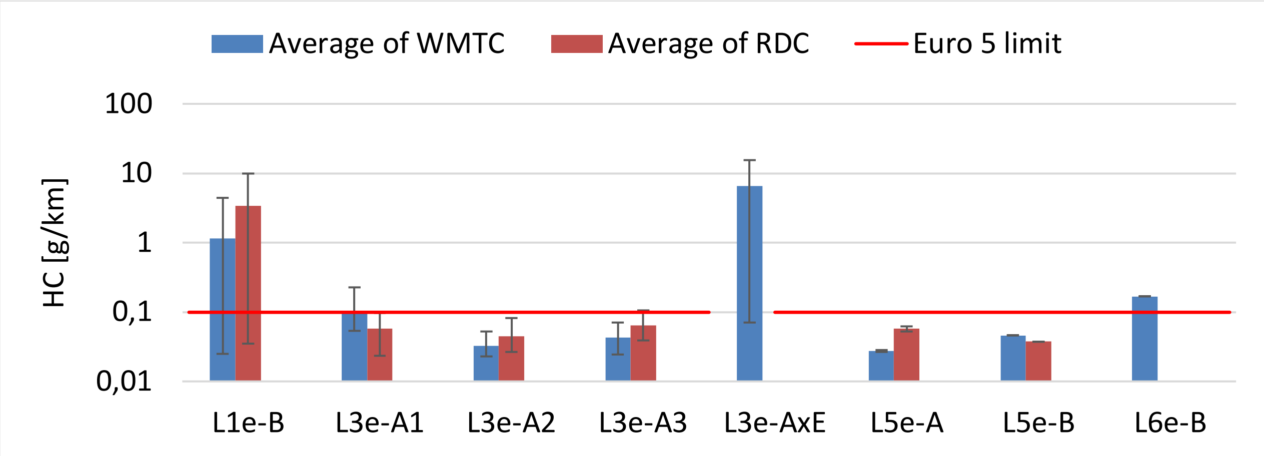

Figure 4: Average HC emissions per category and type of test including standard deviations[10].

2.1.3 NO_x emissions

In type approval tests, the tested L6e-B vehicles were found to have extremely high NO_x emissions, while the rest of vehicle categories had average NO_x emissions lower than the Euro 5 limit. In most vehicle categories average RDC and RDE NO_x emission levels were higher than type approval test NOx levels, suggesting that type approval under-represents somewhat the real-world NO_x emissions of the vehicles. The smaller motorcycle classes L3-A1 and L3-A2 show an exceedance of NOx emission in the RDE tests, same for L5e-A vehicles.

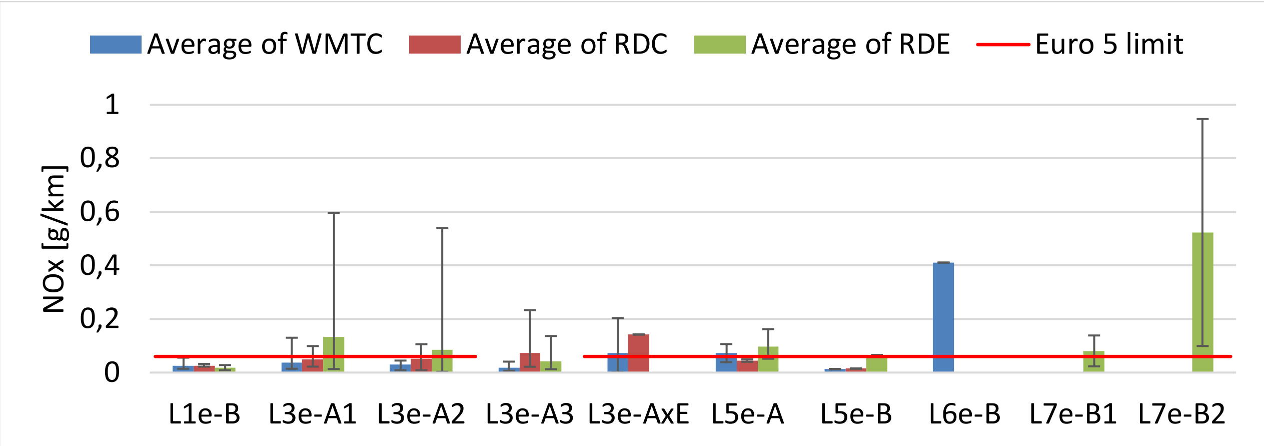

Figure 5: Average NO_x emissions per category and type of test[10].

2.2 Non-regulated gaseous and particulate emission

Besides the regulated emission components, CO_2, NH_3 and particulate number were measured. These emission components are not regulated in the current regulation EURO5 / EURO5+ but are of interest due to the environmental impact and the consideration in other emission regulations. In the NH3 emission graph, for which

[10] L3e-AxE is limited with HC + NOx.

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no limit is currently in force for L-category vehicles, the proposed Euro 7 limit for passenger cars is shown with a horizontal line.

2.2.1 CO_2 emissions

In Figure 6 the emission levels are shown together with the passenger car fleet limit of 2025. This limit is only indicative, as it is a limit for the OEM`s fleet and considers an average over diverse vehicles with lower and higher CO_2 emission and BEV and Hybrid vehicles.

In general, it was found that the bigger the bike the higher the CO_2 emission is, which is to be expected as the power demand for the test cycles increases with the weight. In WMTC most categories are lower than the fleet limit, but bigger vehicles (L7, L3e-A3) are higher than the limit, indicating that in case of a CO_2 regulation, there might arise an issue for manufacturers who have a high share of bigger vehicles. Average RDE CO_2 levels are always higher than average type approval test CO_2 levels, so type approval underestimates real-world CO_2 emissions.

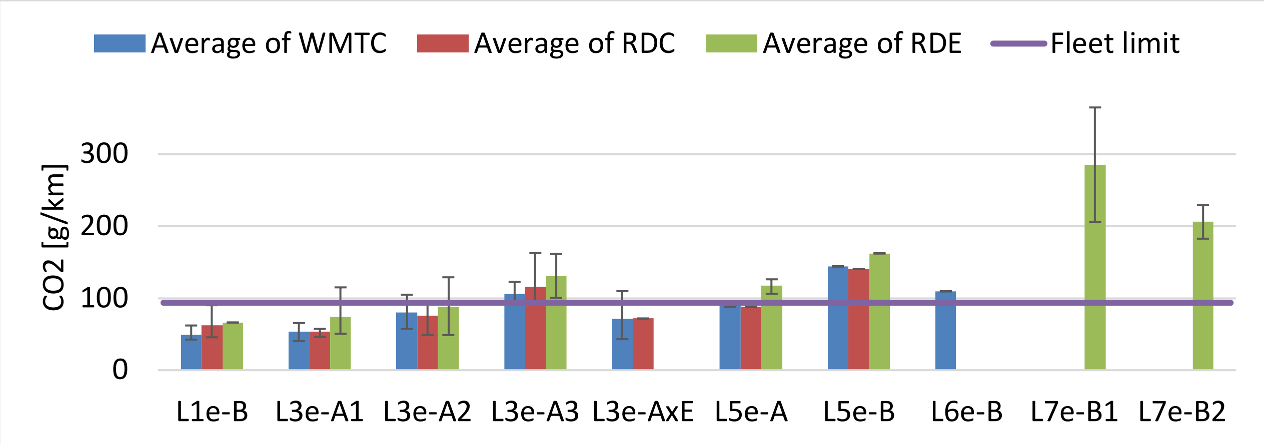

Figure 6: Average CO_2 emissions per category and type of test.

2.2.2 NH_3 emissions

NH_3 is currently not regulated, therefore the discussed emission level of the EURO 7 passenger car proposal[11] is shown as indication. In Figure 7 it is shown, that the average RDE & RDC NH_3 levels were always higher than average type approval test NH_3 levels, so type approval under-represents real-world vehicle NH_3 emissions. Compared to the discussed Euro 7 passenger car NH3 emission level (passenger car 60mg/km lab measurement & 85 mg/km RDE measurement [3]), almost all L-cat vehicles (excluding L7e) had lower NH_3 emissions under all type approval tests. RDE & RDC NH_3 levels for L3e-A1 and L3e-A2 were higher than the discussed NH_3 emission limit.

[11] NH3 discussed but not taken into account for the final EURO 7 LDV standard

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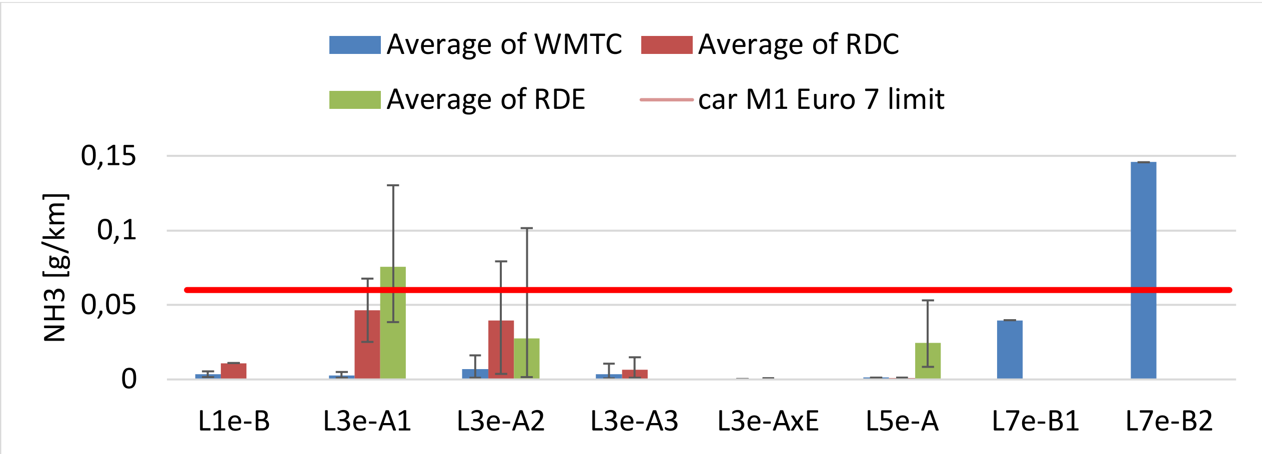

Figure 7: Average NH_3 emissions per category and type of test.

2.2.3 PN emissions

The following figures depict the average emission levels for PN10 of a sub-group of the tested vehicles per category and type of test. The sub-group of vehicles selected are Euro 5 and Euro 5+ vehicles which are not tampered. No PN emission limit is currently in force for L-category vehicles, thus for reference, the Euro 5/6 limit of passenger cars is shown with a horizontal line. It has to be mentioned, that the passenger car limit is currently valid for PN23. Comparison measurements [4] show that L-category vehicles have a PN peak in the region of 23nm, resulting in a major cut-off of smaller particles. When measuring particles with 10nm cut-off a higher particle number results. It can be seen (Figure 8) that compared to the passenger cars Euro 5&6 PN limit, the L-category vehicles have higher average PN emissions in type approval tests. For RDC tests these values increase, while smaller motorcycles have considerably higher PN emission than bigger ones.

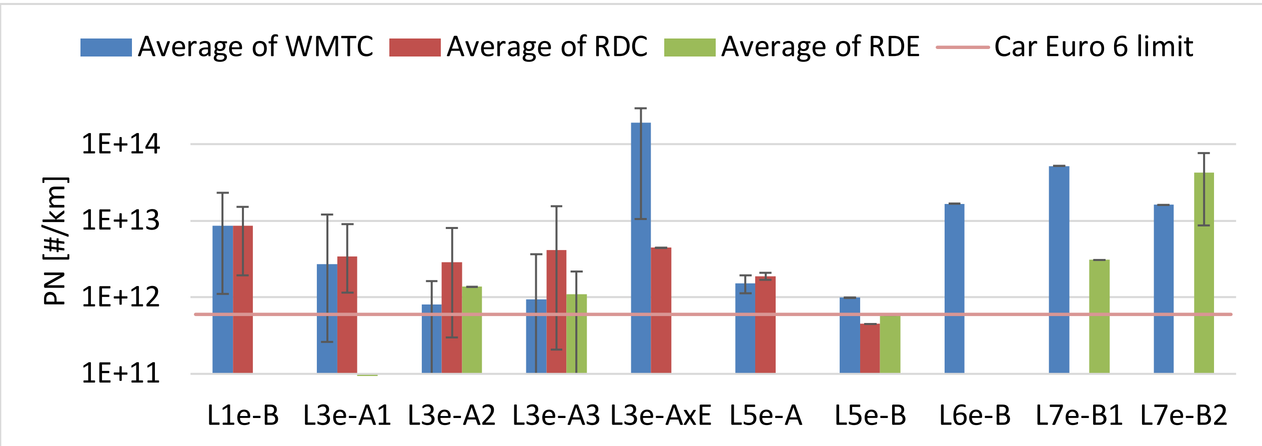

Figure 8: Average PN emissions per category and type of test.

2.2.4 PM emissions

Particulate matter (PM) emissions are commonly known to be relevant for Compression Ignition (CI) engines and Positive Ignition (PI) engines using Direct Injection. L-Category vehicle propulsion systems use typically PI engines with port injection. As the measurement results show, also these engine types can emit high levels of PM in the type approval test, even higher in RDE tests. Differences between the L-Category engine size classes occur with smaller engine capacities having lower average values than bigger engines. Two-stroke engines emit highest

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values. In Figure 9 the distribution of PN/PM emission for various L-Category vehicles is shown together with the EURO 5 PM limit for CI & PI DI engines as well as EURO 7 passenger car PN limit as reference.

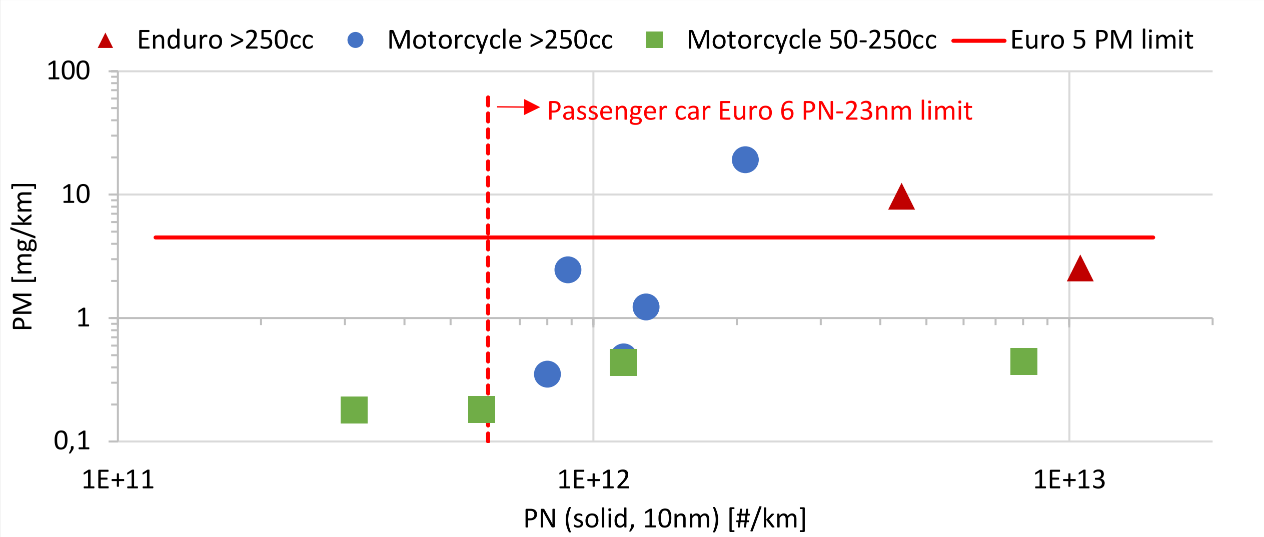

Figure 9: PN/PM diagram for different L-Category vehicles with EURO 5 PM limit for CI & PI DI engines as well as EURO 7 passenger car PN limit (double log display)

2.3 Observations regarding the difference in operating area between laboratory and real-world measurements

During the different laboratory driving tests according to the type approval regulation and real drive cycles as well as during on-road tests, the speed and acceleration trace was recorded. Out of these data several key figures were extracted for all tested vehicles and averaged for the single vehicle categories. Amongst others these are:

- time distribution of speed vs. positive acceleration
- time distribution of engine speed vs. power (engine operation map)
- the 95 percentiles of velocity time positive acceleration $(v*a_{pos})^{95}$ over vehicle speed.

The latter value was used in EURO 6 passenger car regulation for the validity definition of the RDE cycle giving an upper boundary to avoid extreme driving situations.

Exemplarily in Figure 10 the coverage of the different driving cycles of the full engine operation map is shown for a L3e-A3 motorcycle. Clearly visible is the fact, that the WMTC cycle only covers a small area of the operation map, the RDC and standard RDE cover a larger area but only the extreme RDE* cover almost all of the operation map. In Figure 11 the $v*a_{pos}$ of the same 4 different driving cycles / tests in comparison to the EURO 6 passenger car limit (dashed line) is shown over the three sections urban, rural and highway. While the WMTC and the RDC cycles are below or slightly above the passenger car limit, the RDE and especially RDE* are far above the typical passenger car behaviour.

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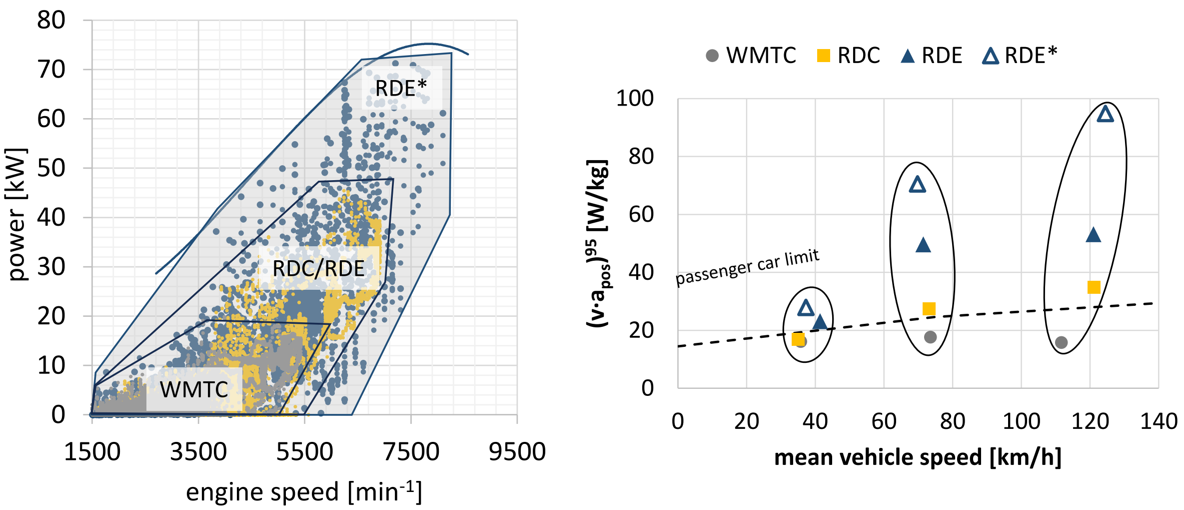

Figure 10: Operating map coverage of type approval (WMTC), real drive cycle lab (RDC), on-road real world trip RDE and extreme driving RDE trip for a L3e-A3 vehicle. [5]

Looking at the time distribution of the average vehicle speed vs. the positive acceleration of the type approval test cycle WMTC 3-2 in comparison to the RDE trip for the L3e-A3 category, it is visible that the vehicle is operated in WMTC with considerably lower acceleration and speeds than in RDE trips.

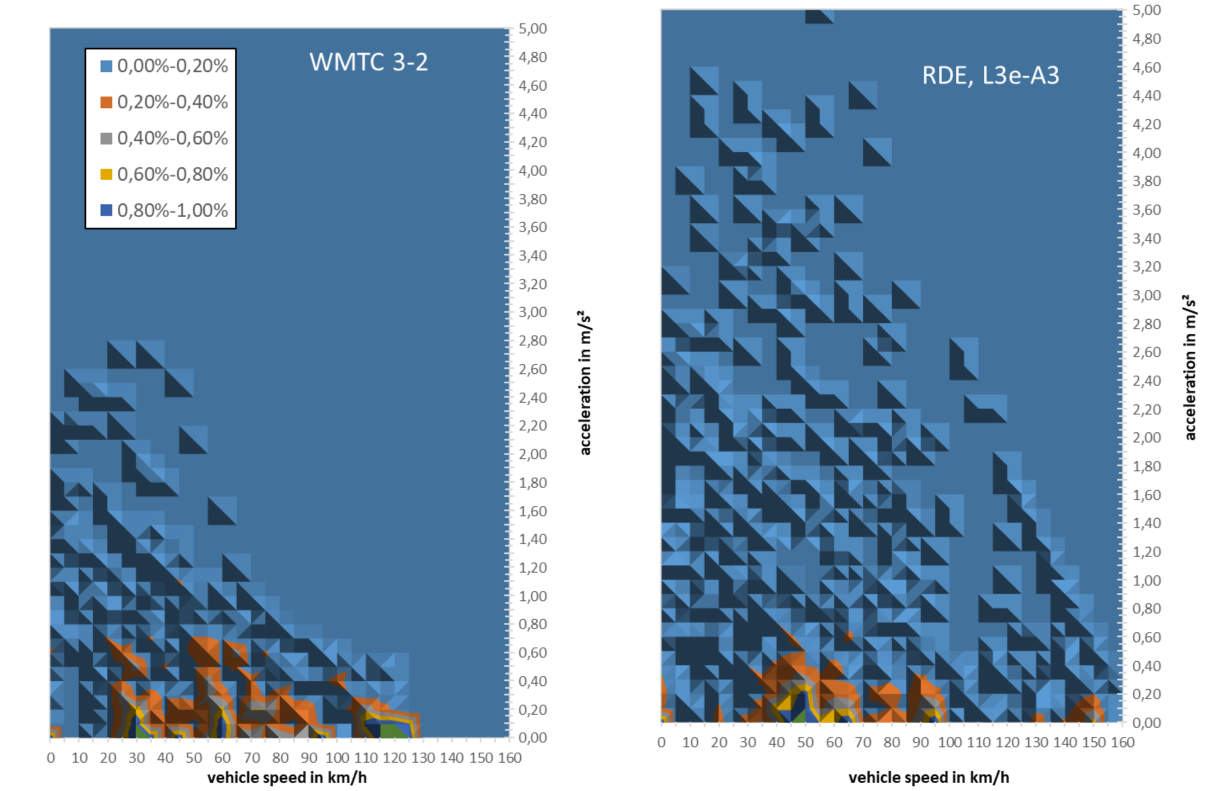

Figure 11: Time distribution Average speed vs. positive acceleration data of L3e-A3 in type approval test (WMTC) and RDE test.

The above shown graphs are similar for the other L-category vehicles. It is clear, that the type approval test does not correspond to real world driving with respect to speed, acceleration and coverage of the engine operation map.

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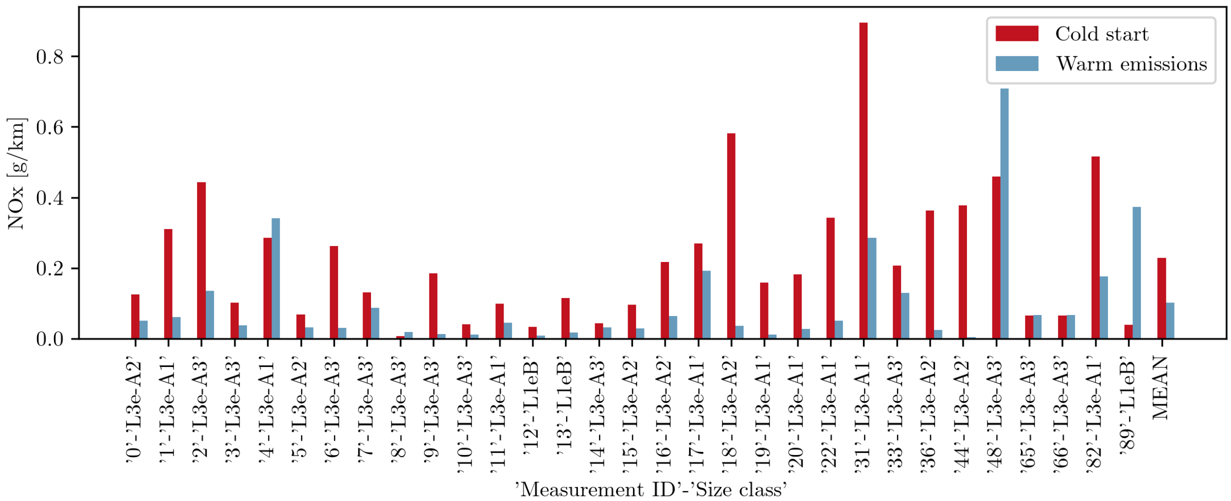
2.4 High emission events

As explained in 1.1.2, an analysis regarding the contribution of specific driving situations and driving events to high emission was performed. Until now, three events were identified with relevant contribution: cold start, acceleration from stand-still and transition from constant speed or acceleration phases to deceleration phases. In the following paragraphs the results of the analysis are given to underpin the findings in 2.6. The full analysis can be found in Deliverable 3.5 chapter 4.5.2.

2.4.1 Cold start

A total of 31 (NOx), 26 (CO) and 9 (HC) cold start events were extracted from the LENS database for analysis. The corresponding average pollutant emissions (in g/s and g/km) were calculated for both the cold start periods and the warm part of each measurement12. The cold start period was defined using the engine coolant temperature and the following first 50 seconds of the measurement. If the total time of the measurement is less than 1000 seconds, the measurement is not considered for the cold start analysis. To ensure that only actual driving behavior was analyzed, data from the beginning of the measurement was excluded if the vehicle velocity was below 1 km/h. This step ensured that the cold start analysis focused on periods of active vehicle operation.

These results including the excess emissions are presented in Figure 12, Figure 13 and Figure 14. More information about each individual measurement uniquely characterised by its measurement ID can be found in Table 2.



[12] The cold start period has been excluded from the total emissions to avoid that the duration of the measurement influences the ratio between cold start and warm emissions.

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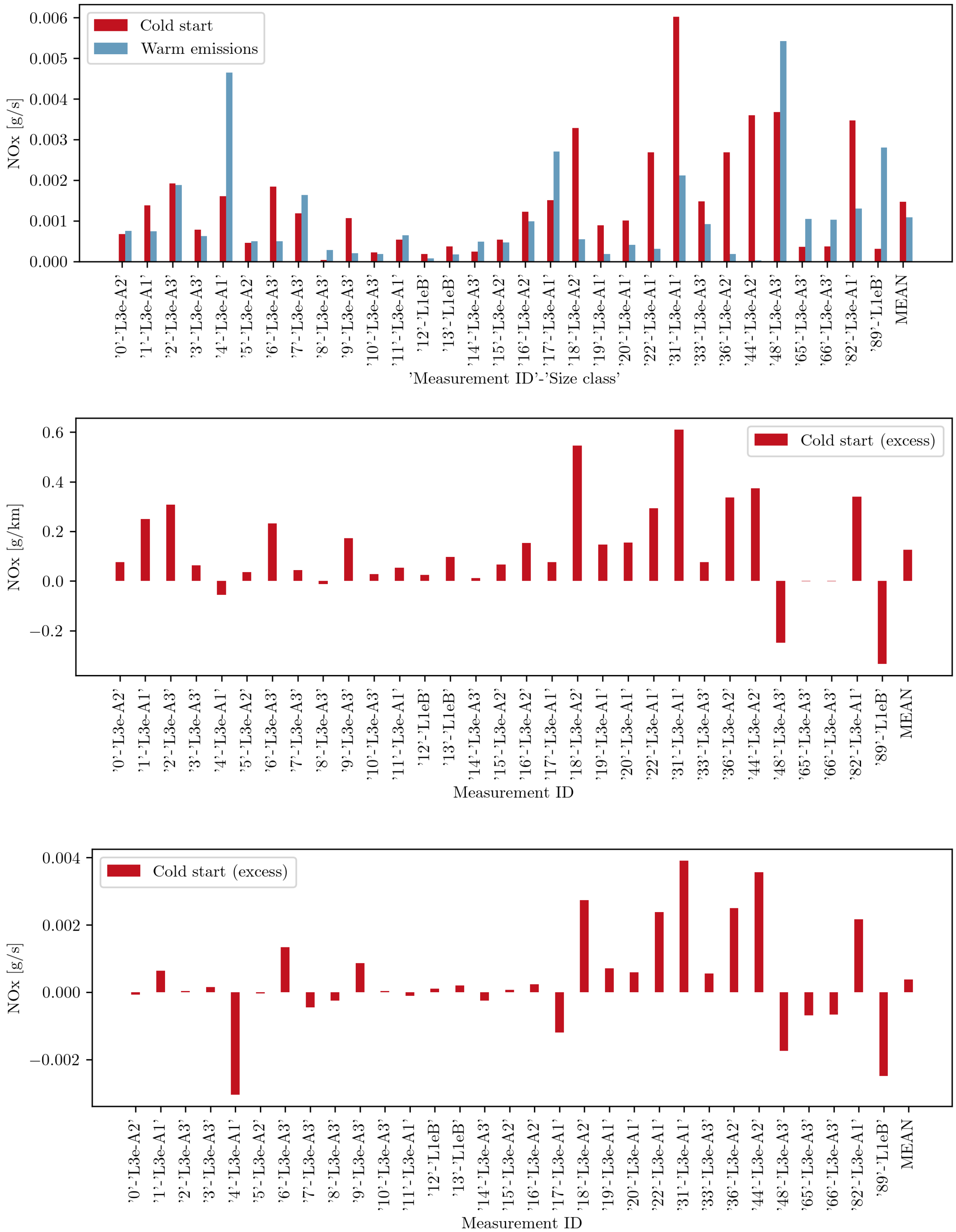

Figure 12: From top to bottom: NOx emissions in g/km, in g/s, excess in g/km and excess in g/s for the cold start events in comparison with the warm part of the **measurements**.

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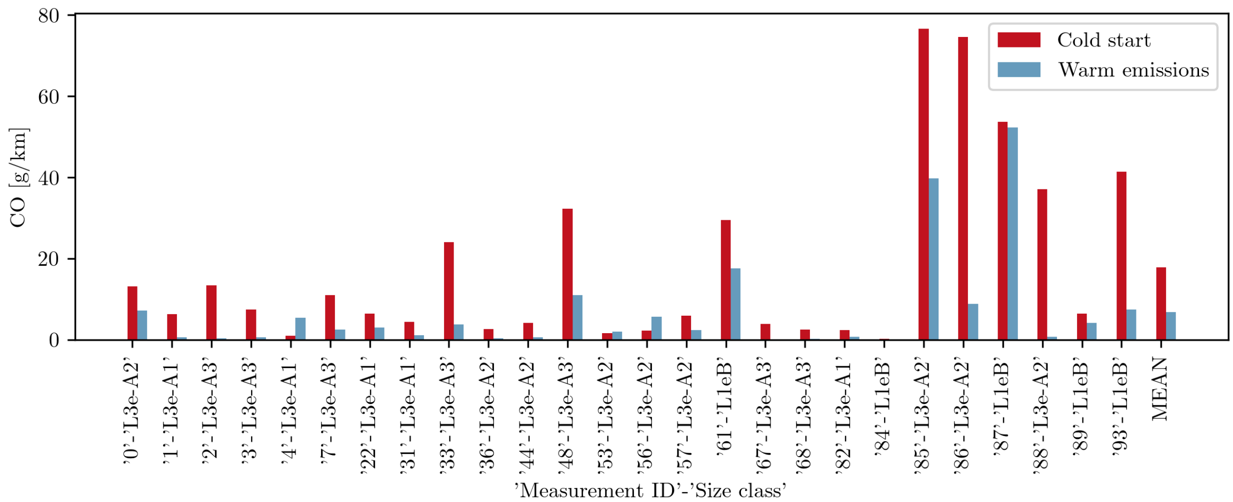

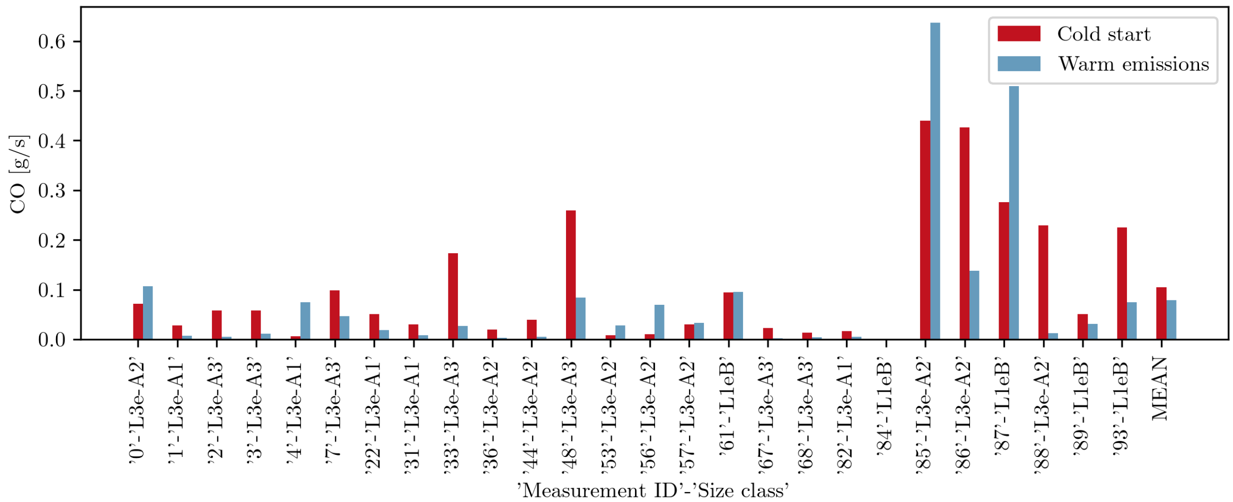

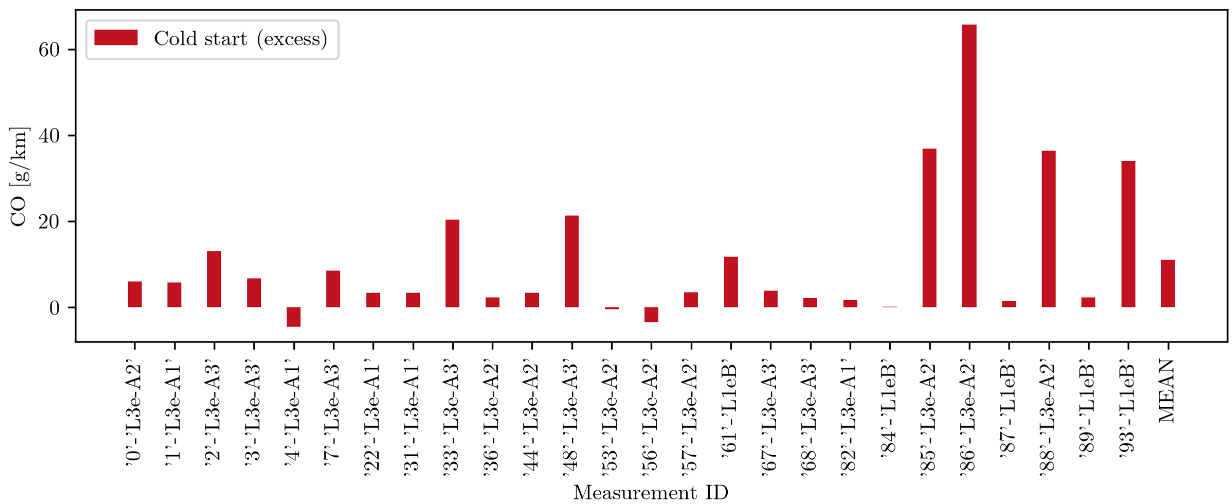

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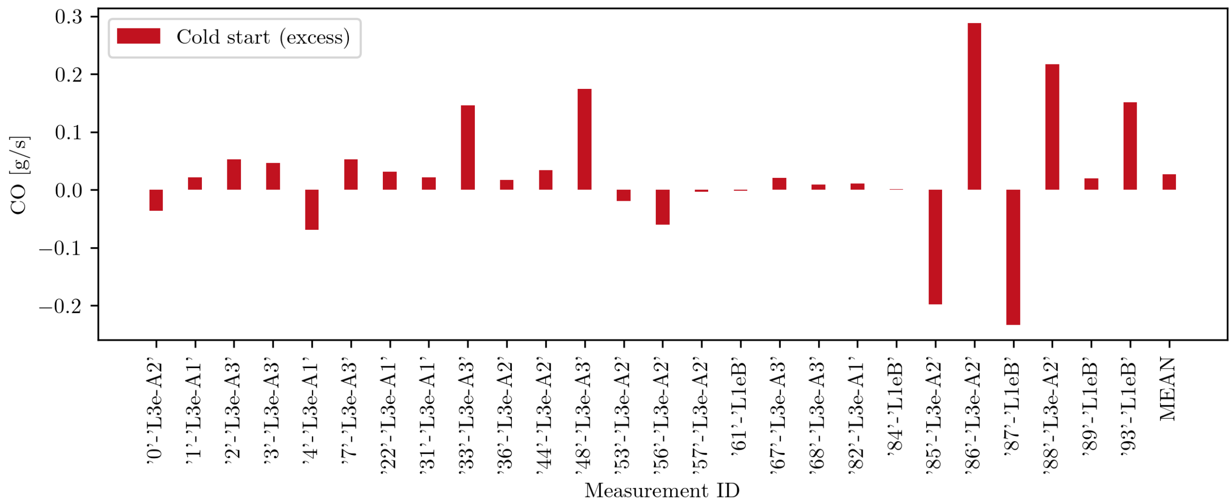
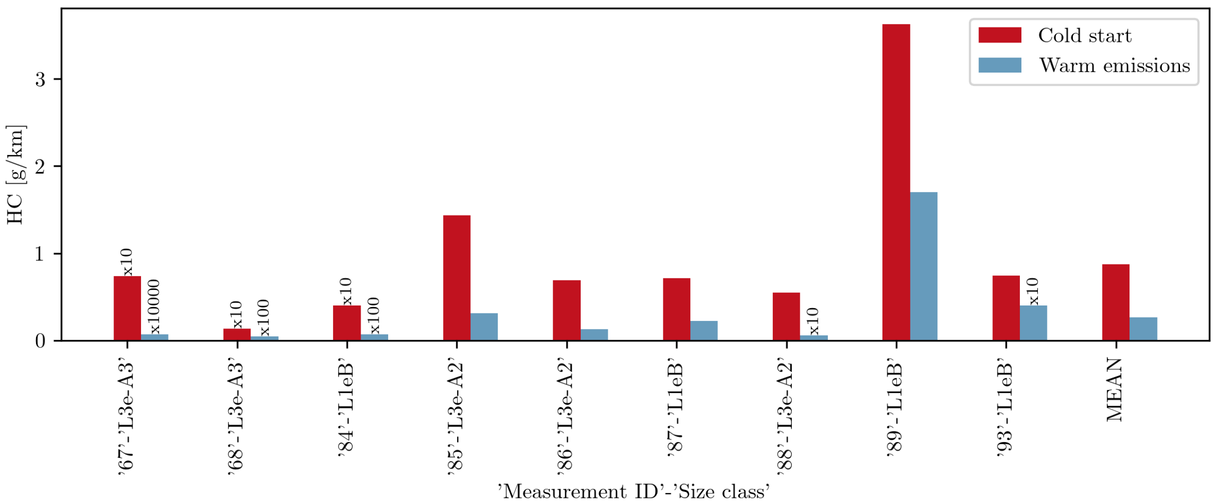
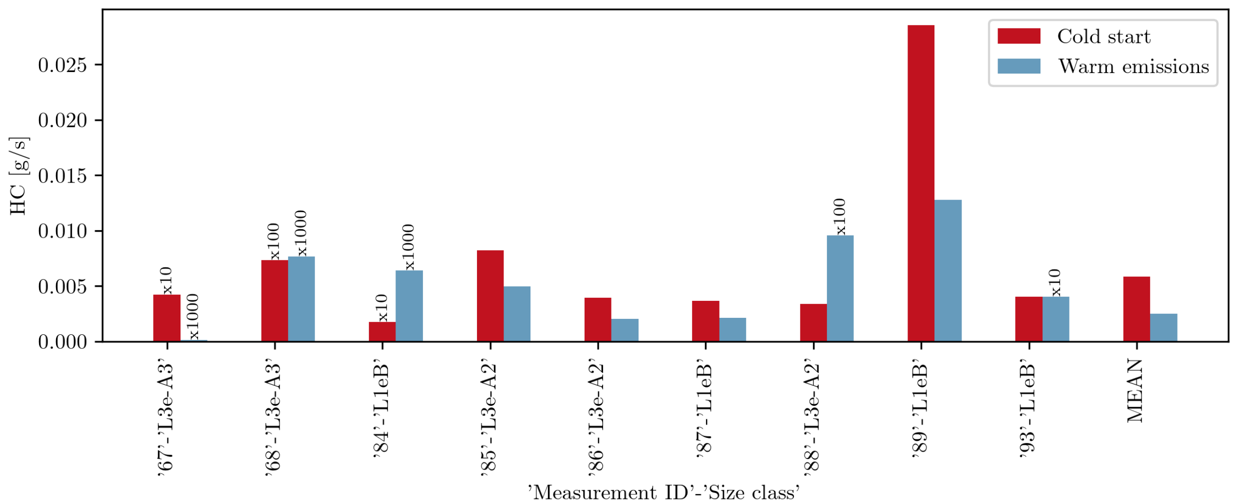


Figure 13: From top to bottom: CO emissions in g/km, g/s, excess in g/km and excess in g/s for the cold start events in comparison with the warm part of the measurements.





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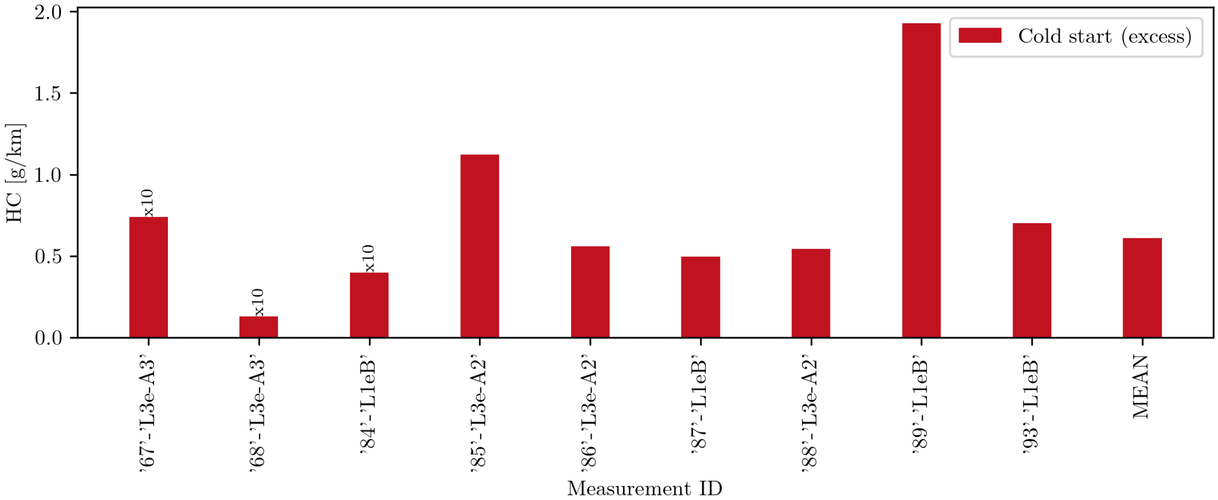

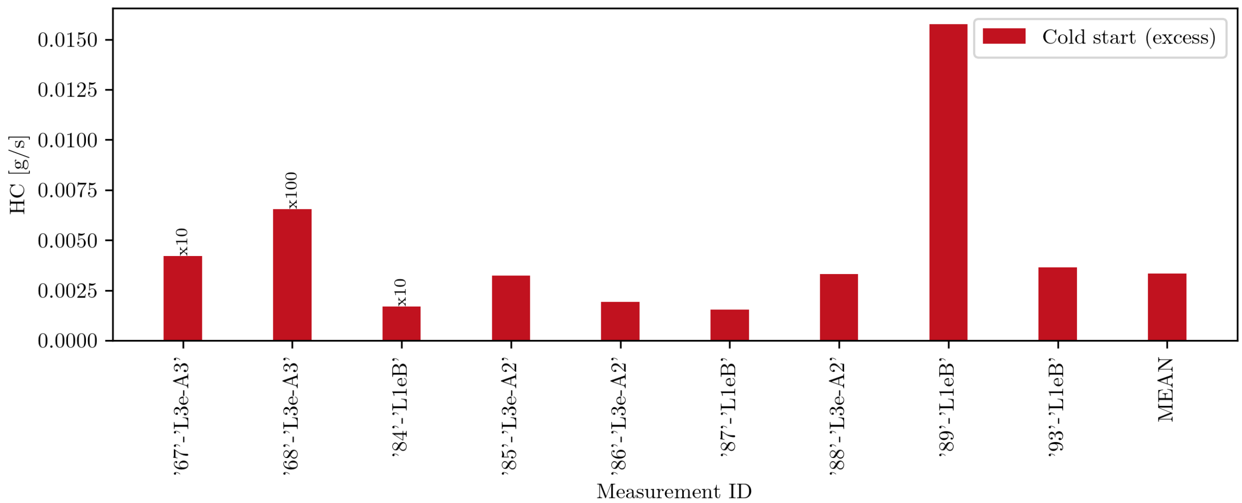

Figure 14: From top to bottom: HC emissions in g/km, g/s, excess in g/km and excess in g/s for the cold start events in comparison with the warm part of the measurements. Note that some values in the figure have been multiplied by a factor of 10, 100, 1000 or 10000 for visualisation purposes, i.e. their true value is 10, 100, 1000 or 10000 times lower than the value displayed in the plot.

The final bar in the plot, labelled "MEAN", represents the average pollutant emissions across all measurements, calculated separately for the cold start events and the warm part of the measurements. Furthermore, the ratio of cold start emissions to total emissions is calculated using two methods:

1. R_1 – First compute the average pollutant emissions separately for cold start events and for the entire measurement duration. The ratio of these two averages is then calculated.
2. R_2 – For each individual measurement, calculate the ratio of cold start emissions to total emissions. Then compute the average of these individual ratios.

These two approaches provide complementary perspectives on the contribution of cold start emissions. Table 1.2 shows the summary of our results for the cold start events. Cold start emissions remain significantly elevated compared to total emissions, but the magnitude varies by emitter category. Overall, cold start NOx emissions are approximately 2.2 to 7.0 times higher, CO emissions are 2.6 to 9.0times higher, and HC emissions are at least

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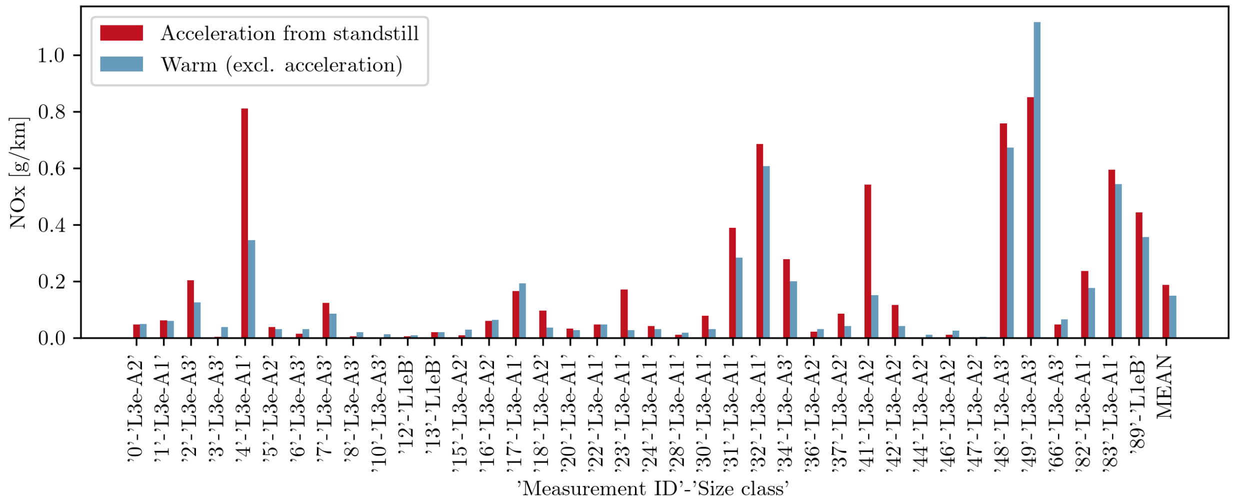
2.3 times higher than their respective total emissions (R2 is not presented as it is very high due to low warm emissions in one measurement). Calculated ratios tend to be higher at the level of g/km than at the level of g/s. These results highlight the disproportionate impact of cold start events.

Table 2: Summary of the results from the cold start events.

Parameter	**Emissions in [mg/km]**			**Emissions in [mg/s]**		
	NOx	CO	HC	NOx	CO	HC
Mean cold start	229 ± 36 mg/km	17875 ± 4363 mg/km	876 ± 376 mg/km	1.5 ± 0.2 mg/s	105 ± 25 mg/s	5.8 ± 3.0 mg/s
Mean warm	102 ± 27 mg/km	6882 ± 2426 mg/km	268 ± 183 mg/km	1.1 ± 0.2 mg/s	78 ± 30 mg/s	2.5 ± 1.4 mg/s
$\boldsymbol{R_1}$	2.2	2.6	3.3	1.3	1.3	2.3
$\boldsymbol{R_2}$	7.0	9.0	-	6.0	4.3	-
Excess emissions	126 ± 35 mg/km	10993 ± 3159 mg/km	608 ± 204 mg/km	0.4 ± 0.3 mg/s	27 ± 22 mg/s	3.3 ± 1.6 mg/s

2.4.2 Acceleration from standstill

A total of 38 (NOx), 52 (CO) and 4 (HC) "measurements with at least one acceleration event have been found in the LENS DB. The corresponding NOx, CO and HC emissions in g/km are shown in Figure 15, Figure 16 and Figure 17. More information about each individual measurement uniquely characterised by its measurement ID can be found in Table 3. The final bar in the plot, labelled "MEAN", represents the average pollutant emissions across all measurements, calculated separately for the "acceleration from standstill" events and the total measurement durations.



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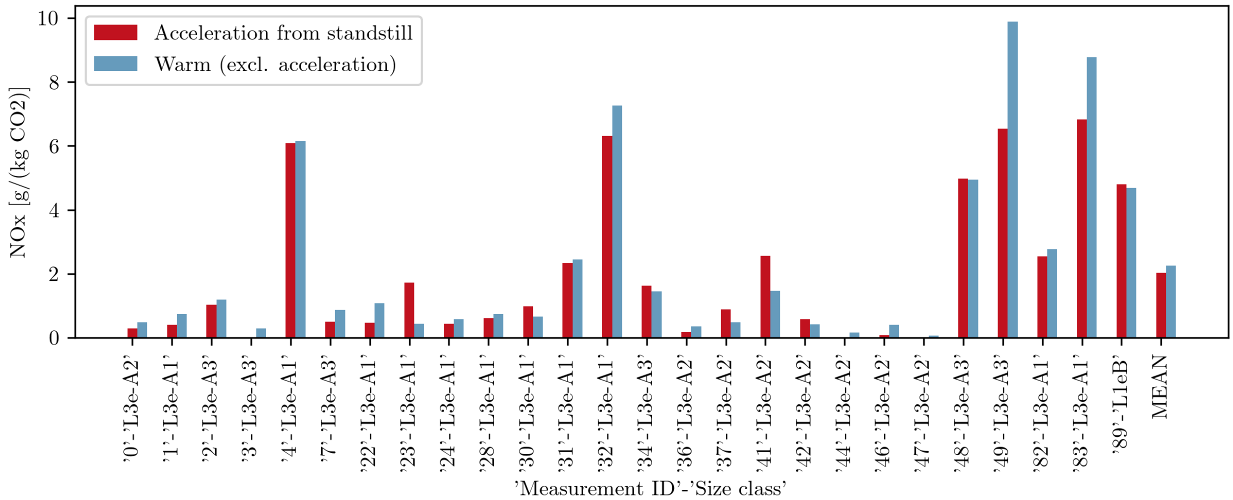

Figure 15: NOx emissions in g/km and g/(kg CO2) for the "Acceleration from standstill" events in comparison with the NOx emissions of the warm emissions (excluding acceleration from standstill events).

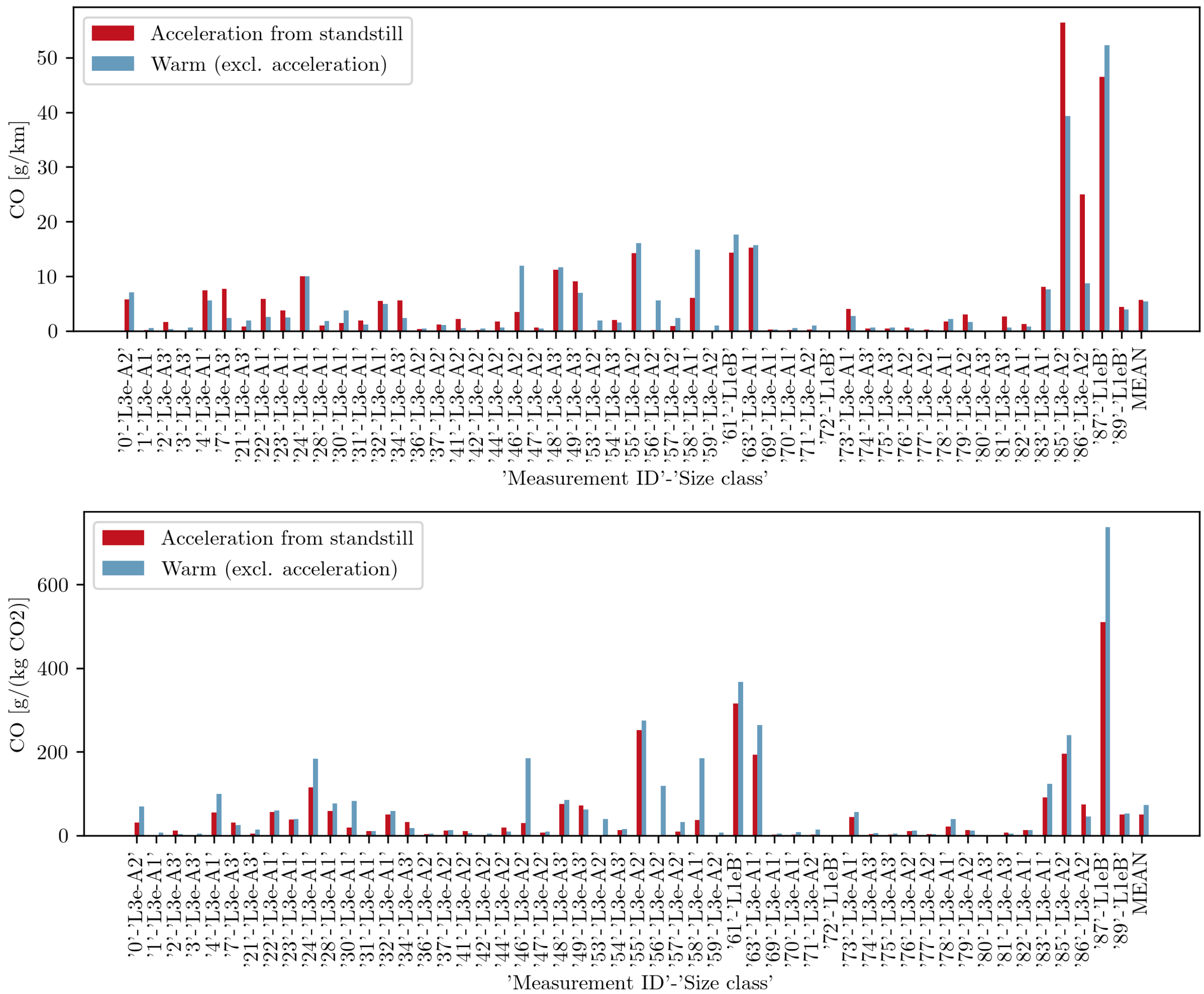

Figure 16: CO emissions in g/km and g/(kg CO2) for the "Acceleration from standstill" events in comparison with the CO emissions of the warm emissions (excluding acceleration from standstill events).

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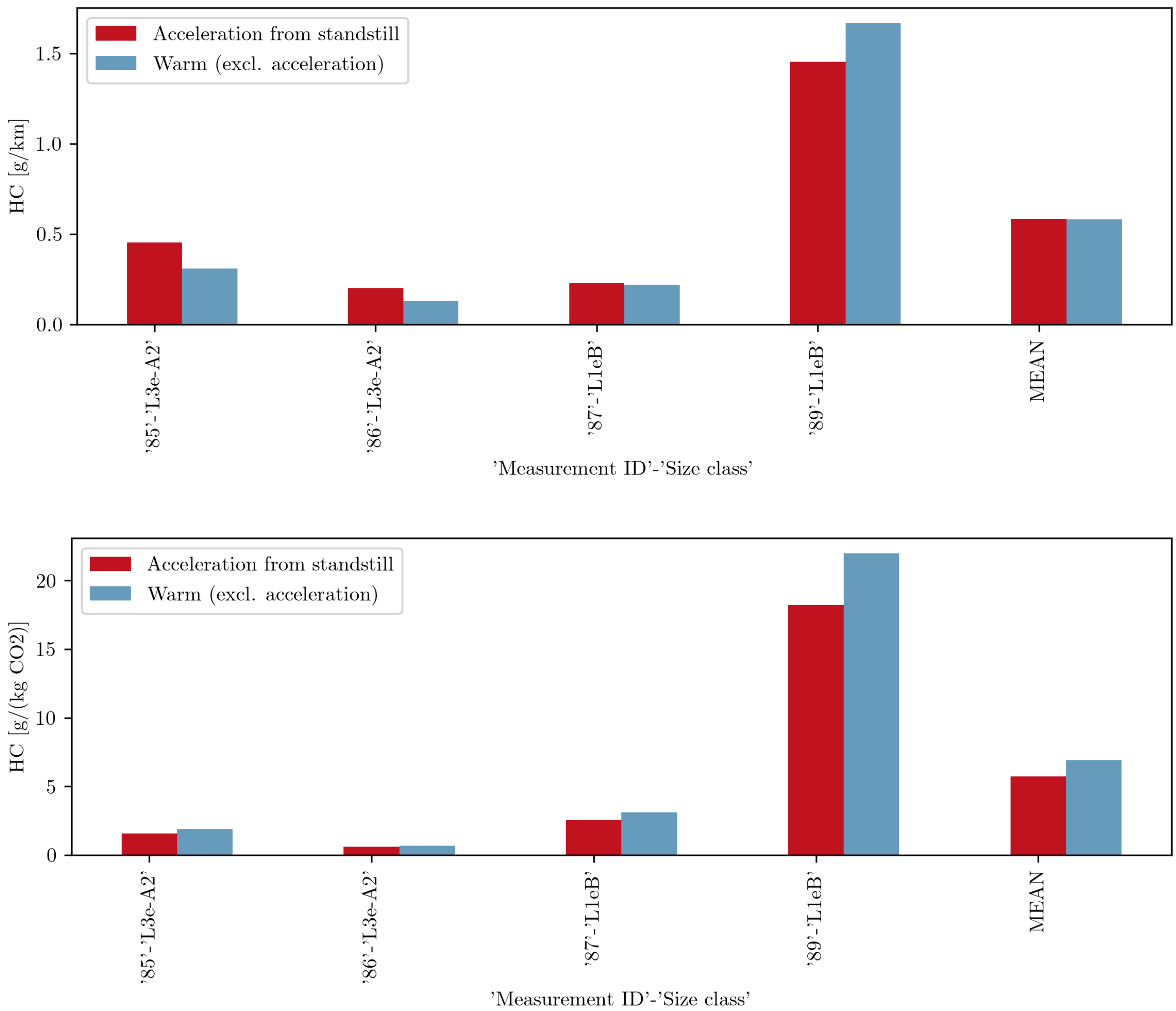

Figure 17: HC emissions in g/km and g/(kg CO2) for the "Acceleration from standstill" events in comparison with the HC emissions of the warm emissions (excluding acceleration from standstill events).

The summary of the "acceleration from standstill" events are shown in Table 1.3. The increase in emissions in g/kg CO_2 during these events is relatively modest: NOx emissions are approximately 1.3 times higher, CO emissions are 1.1 to 1.2 times higher, and HC emissions are 1.0 to 1.5 times higher compared to total emissions The NOx emissions in g/(kg CO2) during the acceleration from standstill events are 0.9 times lower than the warm emissions and the C) emissions in g/(kg CO2), are lower by a factor of 0.7 to 0.8, and the HC emissions in g/(kg CO2) are a factor 0.8 times lower. These findings indicate that acceleration from a standstill leads to increased emissions when measured in g/km, but this effect is not observed when emissions are measured in g/(kg CO2).

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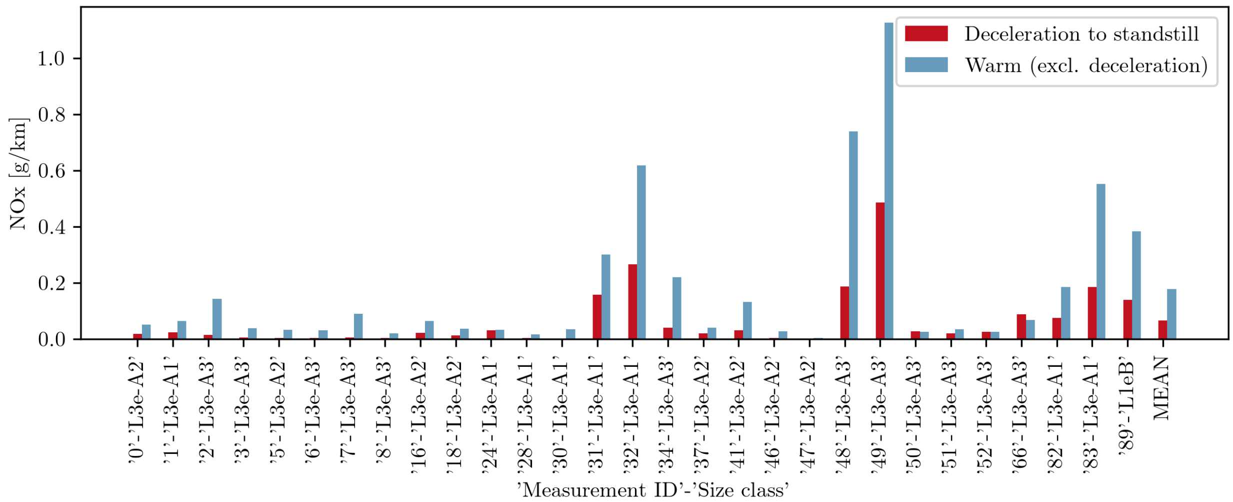
Table 3: Summary of the results from the "acceleration from standstill" events.

Parameter	Emissions in [mg/km]			Emissions in [g/kg CO2]		
	NOx	CO	HC	NOx	CO	HC
Mean acceleration from standstill	187 ± 41 mg/km	5735 ± 1462 mg/km	584 ± 295 mg/km	2.0 ± 0.5 g/(kg CO2)	50 ± 13 g/(kg CO2)	5.7 ± 4.2 g/(kg CO2)
Mean warm	149 ± 38 mg/km	5443 ± 1314 mg/km	582 ± 364 mg/km	2.3 ± 0.6 g/(kg CO2)	74 ± 17 g/(kg CO2)	6.9 ± 5.1 g/(kg CO2)
R_1	1.3	1.1	1.0	0.9	0.7	0.8
R_2	1.3	1.2	1.5	0.9	0.8	0.8

2.4.3 Transition from constant speed or acceleration phases to deceleration phases

A total of 29 (NOx), 48 (CO) and 4 (HC) "measurements with at least one deceleration event have been found in the LENS DB. The corresponding NOx, CO and HC emissions in g/km are shown in Figure 18, Figure 19, and Figure 20. More information about each individual measurement uniquely characterised by its measurement ID can be found in Table 4. Consistent with the approach used in the previous section, the final bar in the plot labelled "MEAN" represents the average pollutant emissions across all deceleration events.



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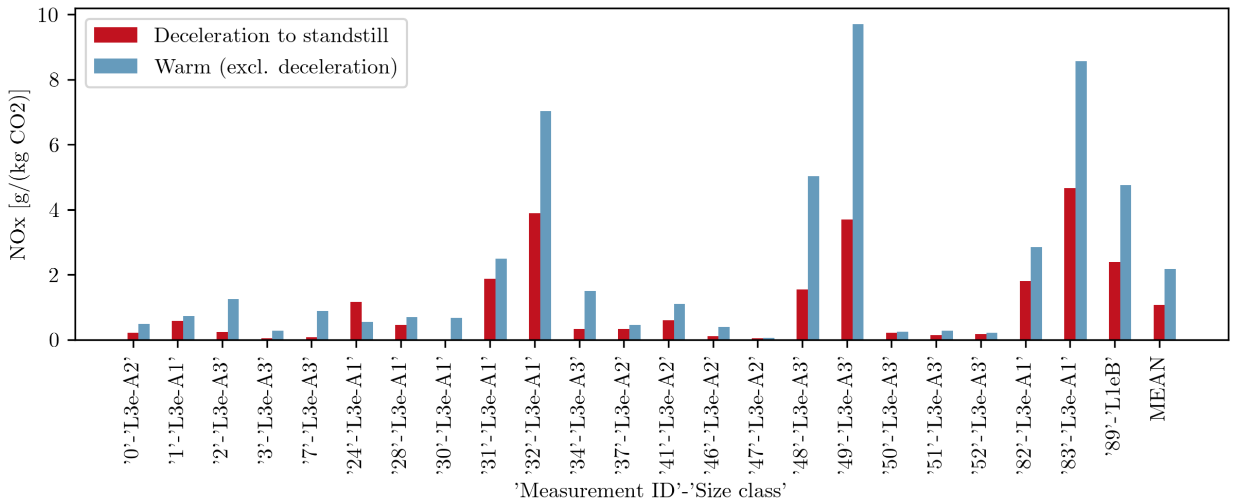
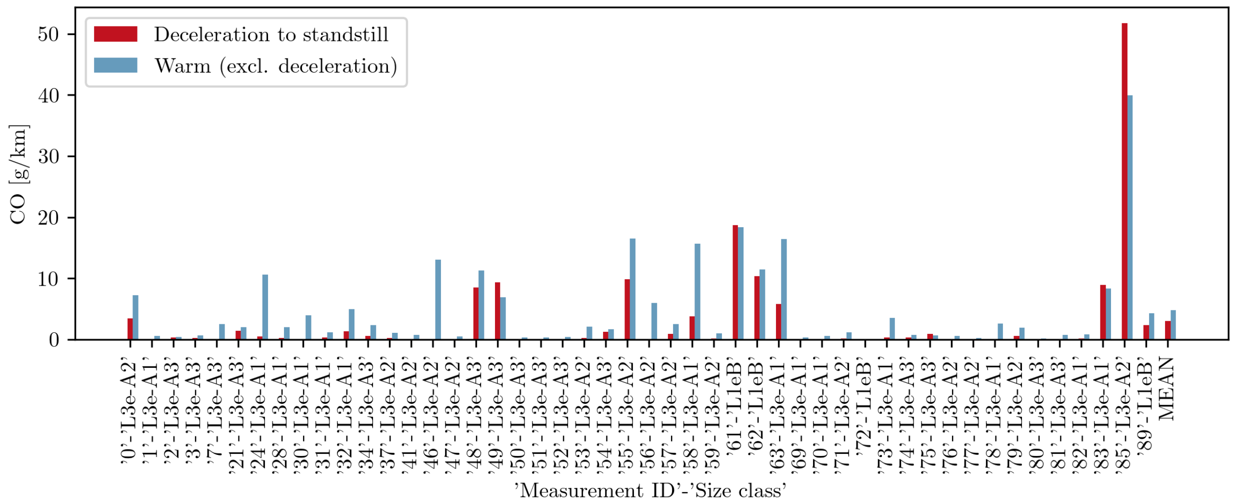


Figure 18: NOx emissions in g/km and g/(kg CO2) for the "deceleration to standstill" events in comparison with the NOx emissions of the warm emissions (excluding deceleration to standstill events).



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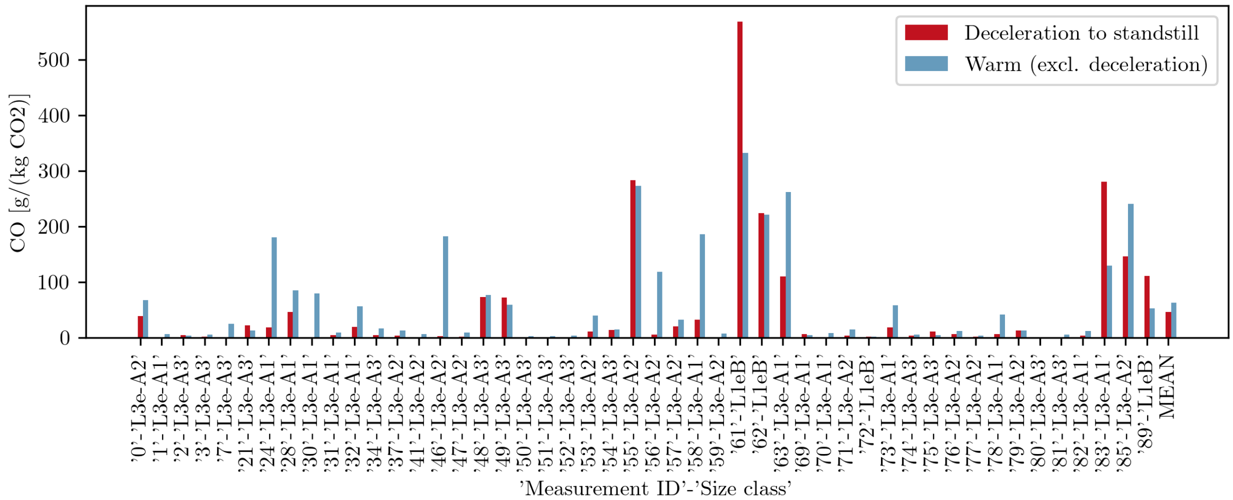
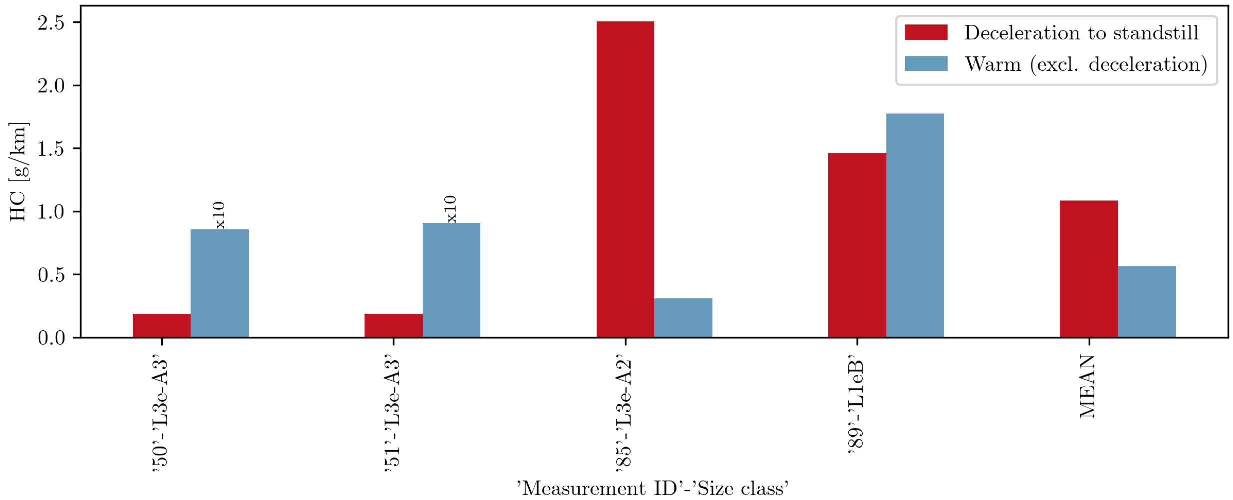


Figure 19: CO emissions in g/km and g/(kg CO2) for the "deceleration to standstill" events in comparison with the CO emissions of the warm emissions (excluding deceleration to standstill events).



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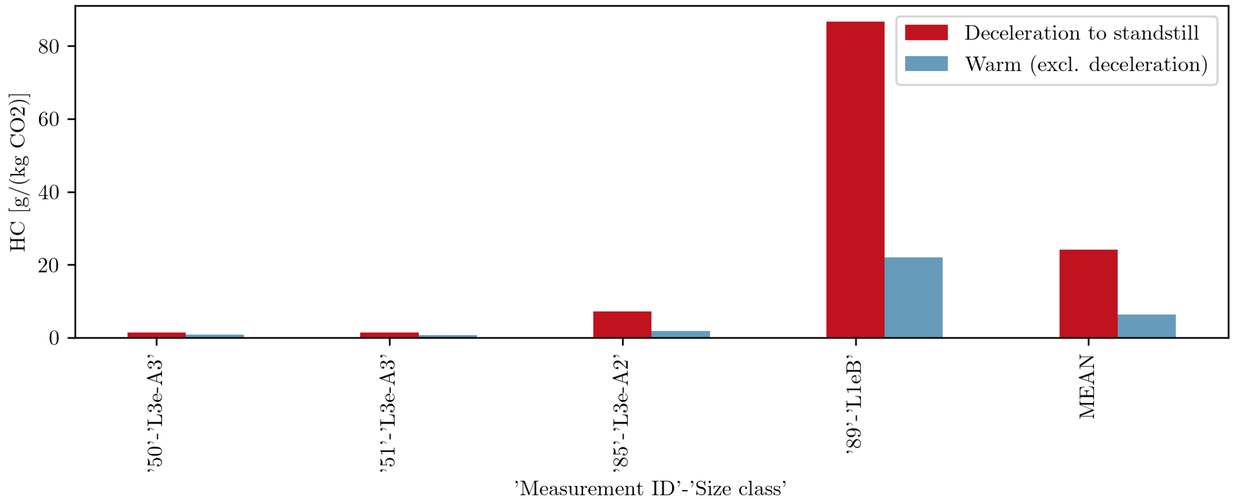

Figure 20: HC emissions in g/km and g/(kg CO2) for the "deceleration to standstill" events in comparison with the HC emissions of the warm emissions (excluding deceleration to standstill events.

The summary of the "deceleration from standstill" events are shown in Table 1.4. NOx and CO emissions in g/km during these events are notably lower than their respective warm emissions, with NOx reduced by a factor of 0.4 and CO by 0.4 to 0.6. HC emissions, however, appear 1.9 to 3.3 times higher. Similarly, the NOx and CO emissions in g/kg CO2 are lower by a factor of 0.5 to 0.6 and 0.6 to 0.7, respectively. The HC emissions in g/kg CO2 appear 2.8 to 3.8 times higher. It is important to note that the number of measurements for HC during deceleration events is fairly low, resulting in low statistical confidence. Therefore, the HC values should be interpreted with caution, as they may not fully represent typical emission behaviour during these events.

Table 4: Summary of the results from the "deceleration to standstill" events.

Parameter	Emissions in [mg/km]			Emissions in [g/kg CO2]		
	NOx	CO	HC	NOx	CO	HC
Mean deceleration to standstill	66 ± 20mg/km	3005 ± 1175 mg/km	1085 ± 561 mg/km	1.1 ± 0.3 g/kg CO2	46 ± 15 g/kg CO2	24 ± 21 g/kg CO2
Mean warm	177 ± 49mg/km	4830 ± 1048 mg/km	565 ± 407 mg/km	2.2 ± 0.6 g/kg CO2	62 ± 12 g/kg CO2	6.4 ± 5.2 g/kg CO2
R_1	0.4	0.6	1.9	0.5	0.7	3.8
R_2	0.4	0.4	3.3	0.6	0.6	2.8

2.4.4 L3e-A2 CVT detailed analysis

On typical vehicles has been selected with the purpose of better understand the behaviour that a L3e-A2 equipped with CVT transmission could have. On this way both RDC and RDE measurements has been considered.

CO emissions: In Figure 21, CO emissions behaviour against engine load and engine speed are represented. From all the pollutants considered in this analysis, CO has been the most critical one. When operating below 80% engine load and below 80% of its maximum engine speed, CO emissions do not show any problem. When those values are surpassed, CO emissions emerge, reaching punctually 25 g/km. Regarding total values, RDC CO emissions reach 5218.7 mg/km, which means +50x times total averaged unweighted value of WMTC for this same vehicle and 70x times when considering only events above 90 km/h on both measurements.

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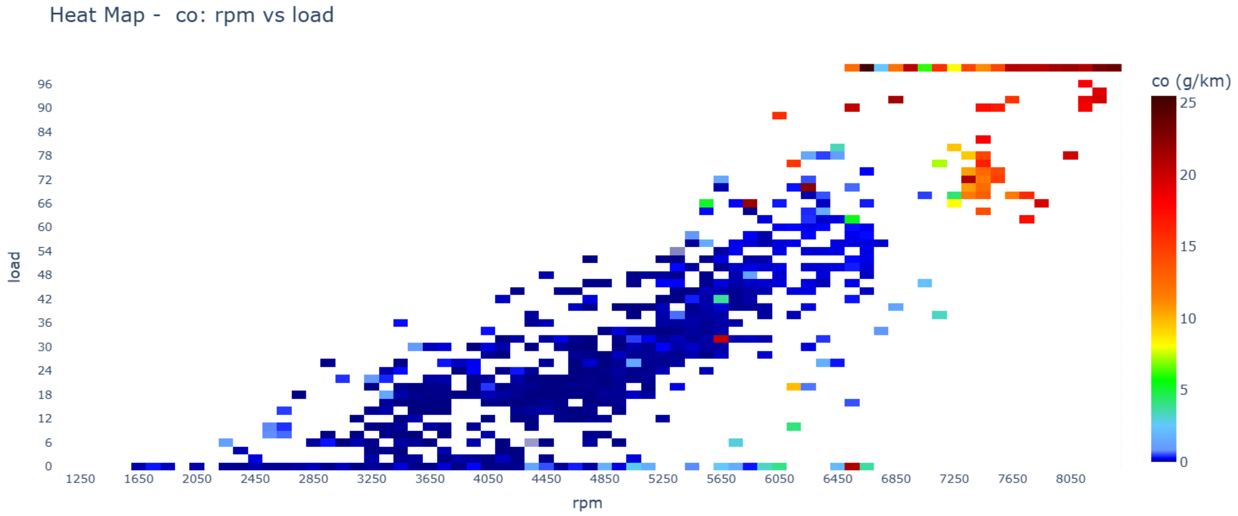

Figure 21: CO emissions (g/km) from L3e-A2 equipped with CVT transmission. RDC and RDE tests are represented.

HC emissions: regarding HC emissions, the same behaviour as for CO is represented in Figure 22, where HC emissions are now represented against engine and vehicle speed. In this case, emissions are better controlled, reaching a maximum value of 300 mg/km. The current regulation limit is 100 mg/km, averaged and weighted for the different test cycle phases. Considering the particular way of operation of CVT transmissions, when accelerating from constant speed, at high engine load, 100% in this case, engine speed increase almost instantly, while the vehicle speed gradually increases. This scenario is clearly shown in Figure 22, where HC emissions get severe due to fuel enrichment, resulting in an increase of HC emissions in the RD cycle of 2x times WLTC total averaged unweighted value, and nearly 10x times when considering only events above 90 km/h.

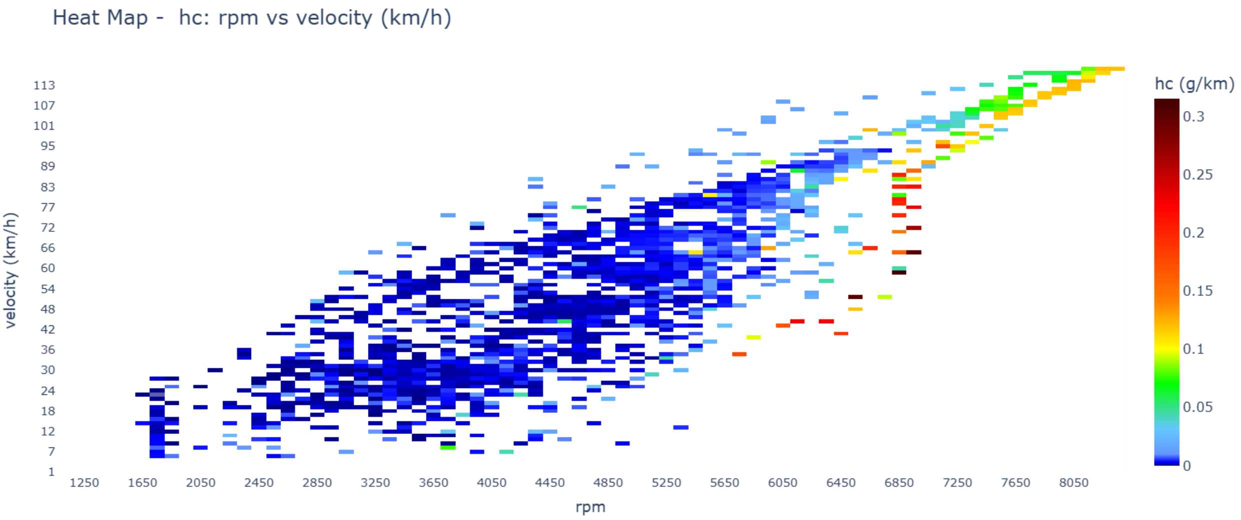

Figure 22: HC emissions (g/km) from L3e-A2 equipped with CVT transmission. RDC and RDE tests are represented

NOx emissions: NOx emissions over engine speed vs. vehicle speed * acceleration are represented in Figure 22. Maximum values obtained reach 0.8 g/km in some specific situations of high accelerations at high RPM. These events only take place in a very specific situation. During the remaining measurements' traces, emissions are

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adequately controlled, resulting in a total value of ~38 mg/km not being a problem since it corresponds to an increase of +30% from WMTC total averaged unweighted value, which is not critical for this kind of vehicles.

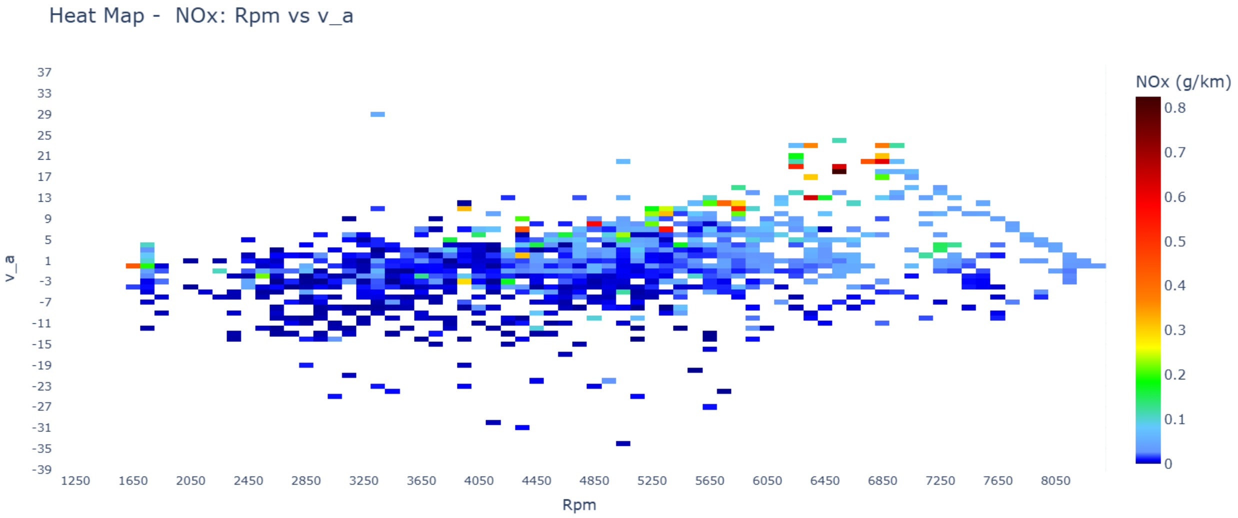

*Figure 23: NOx emissions (g/km) vs v*a from L3e-A2 equipped with CVT transmission. RDC and RDE tests are represented.*

This analysis is revealing where the weaknesses are in the emission control. In D3.5 more detailed information is obtained for other LVs vehicle categories and also the occurrence and severity of these events is identified.

2.5 Determination of real-world running resistance

An analysis regarding the difference between the running resistance on-road and in type approval laboratory conditions has been conducted. A detailed description of the investigations can be found in chapter 7 . For four different vehicles the running resistances were calculated from coast-down experiments. Based on these data a comparison between the measured data from the track experiments and the running resistance curve using the table values of Appendix 5 of EU Regulation No 134/2014 was performed. The graph in Figure 24 shows an example of the running resistances for a BMW R1250 GS Adventure. The blue curve shows the fitted function for the real-world running resistance on the track, while the orange curve shows the corresponding table values, i.e. the prescribed f0 and f2 coefficients based on the table in Appendix 5 of EU Regulation No 134/2014. Results have been extrapolated towards 0 km/h, to show the difference in f0. There is a clear difference between these sets of running resistances, however a direct comparison cannot be made since the coast-down values are applied as target settings on the chassis dynamometer while the table values are directly applied as chassis dynamometer settings. This means that the running resistance of the tire on the roller is missing from the table value curve, as well as the resistances of wheel bearing, secondary drive train (cardan axle, belt or chain) and the outer shaft of the gearbox.

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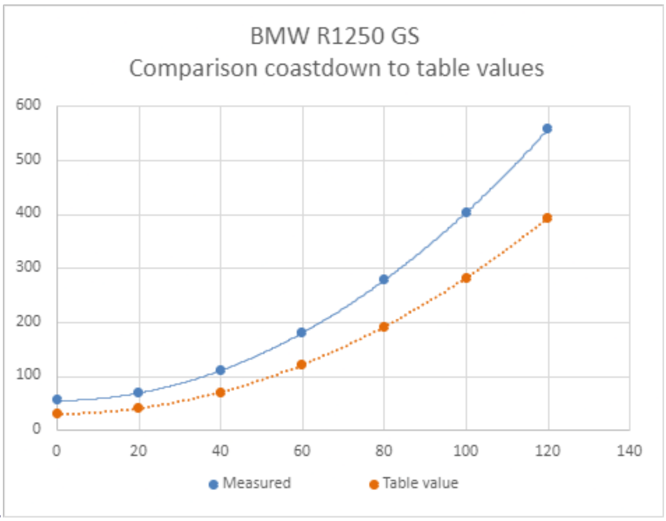

Figure 24: Comparison of coast-down results and table values [2] for BMW R1250 GS Adventure.

2.6 Overall Findings

The observations can be divided in the current type approval results (WMTC) and in RDC and RDE results. For the WMTC results it can be seen that in most cases the regulated emission components CO, NO and HC are within the limits except for the L1e-b category. The non-regulated emission component NH_3 is below the light duty vehicle EURO7 limit, while PN emission are considerably higher than the passenger car EURO6 limit. CO_2 is not regulated as emission component - instead a CO_2 fleet regulation is in force; for 2025 the limit is 93.6 g/km for passenger cars.

Taking a look at the emission results from the more realistic real drive cycle measurements RDC, a different picture can be observed. Almost all vehicle classes exceed the limit for CO by far, except for the biggest two-wheeler category L3e-A3 which is on the limit. NO_x emissions are closer to the limit but not exceeding. Particulate numbers are above the passenger car limit for all categories except for L5e-B.

A similar observation can be drawn for the on-road measurement results of RDE tests, where we see increased emission compared to the WMTC results. It has to be noted, that for the WMTC the three parts are weighted and then summed up, whereas RDC and RDE results are calculated without weighting. This weighting reduces the impact of the first phase with cold start in the WMTC in comparison to the RDC and RDE test and has to be considered for WMTC vs RDE and RDE comparison.

The additional investigations regarding running resistance and high emission events show differences between lab tests and real-world behaviour.

All in all, from the measurements conducted the following conclusions can be derived:

- An operation of the vehicles outside the WMTC area leads to increased emission from almost all vehicle categories and for most emission components. The level rises from WMTC to RDC and RDE results.
- Currently non-regulated emission components like particulate number and NH_3 are considerably above the limit from passenger cars in EURO 6 or EURO 7.
- The L-category class L7-B is scarcely represented in the fleet, instead many vehicles of this type are type-approved as T-category.
- Key Findings from high emission event analysis

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- Cold Start: Pollutant emissions during cold start events were on average multiple times higher than the warm emissions average.
- Acceleration from Standstill: These events showed pollutant emissions up to 1.5 times higher than the warm emissions average.
- Deceleration transitions: NOx and CO emissions are roughly halved, while HC emissions are several times higher than the warm emissions average; however, due to the limited HC data, statistical confidence for HC is low.

These events are frequent in everyday motorcycle use, especially in urban environments, making them highly relevant for regulatory consideration.

Critic results on CO have been identified in 2-stroke L1e-B, and low powered L3e-A1/2 CVTs, when operating at high vehicle speeds and/or high load. Regarding HC emissions, they are also triggered, but lower by two orders of magnitude from CO emissions, except for 2-stroke vehicles, whose emissions are triggered.

- Key findings from road running resistance analysis

Setting the appropriate resistance on a chassis dynamometer to reflect the real-world running resistance of the vehicle on the road is important to measure representative emissions, particularly if CO_2 standards were to be set in the future. The actual procedure of setting the road load at the dyno by using table values based on the vehicle mass has its weaknesses:

  - The table values are directly used, only on the basis of vehicle mass, to define the dyno parameters equivalent inertia mass, rolling resistance and aero drag coefficient.
  - Newly type approved L-category vehicles have considerably different aerodynamic shapes for the same mass class. Super-sport and touring motorcycles might have the same mass yet different aerodynamic resistance. Applying same table values based on the same mass leads to the same running resistance although this is not the case in real world. For some vehicle this leads to an underestimation, for others to an overestimation of the real-world running resistance.
  - The table value dyno setting does not consider the vehicle and dyno specific resistances of the tire-roller contact.
  - The table values have been defined several years ago based on the then existing fleet and reflect the typical and average aerodynamic and running resistance of vehicles at the time. As vehicle design has changed since then, especially concerning the mass to aerodynamic force ratio, these table values are no longer up to date.

- Measured running resistances from a vehicle coast-down cannot be directly compared to the table values since the latter are a chassis dynamometer setting, which means that the resistance of the tires on the rollers will add to the running resistance that the vehicle encounters during a lab test.
- The effect of a higher running resistance could not be verified in a real test. Simulation results from the PHEM[6] model show that an increase in running resistance yields a higher CO_2 emission, but only to some extent.
- The influence of a higher running resistance on the pollutant emissions NO_x, CO and HC could not be verified by measurements on a chassis dynamometer, but the simulations seem to suggest that they behave similarly to the CO_2 emissions. It is recommended that these outcomes be confirmed by chassis-dynamometer measurements.

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From these findings, recommendations for type approval procedure modifications are given in chapter 5. In the next chapter 3 the major principles of the current type approval procedure are explained for reference. Additionally, in chapter 4 a reference to other regulations than the L-category EURO 5 regulation is given.

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3 Current TA regulation for L-category Vehicles

For reference the major principles of the current type approval regulation are described in the following. With respect to the conclusions of chapter 2, focus is given on the Type 1 testing procedure "exhaust emissions after cold start" .

The EU Regulation No 168/2013[7] regulates the approval and market surveillance of two- or three-wheel vehicles and quadricycles. It was supplemented by the Commission delegated EU Regulation No 134/2014 [1] with regard to environmental and propulsion unit performance requirements.

Major aspects regulated are:

- Definition of the vehicle categories (Commission delegated EU Regulation No 134/2014 of 16 December 2013 [1] ANNEX IX, Table 8-1)
- Obligations of the manufacturer regarding the environmental performance of vehicle (Commission delegated EU Regulation No 134/2014 of 16 December 2013 [1] Chapter II)
    - Technical specifications, requirements, and test procedures with respect to the environmental performance of L-category vehicles (Commission delegated EU Regulation No 134/2014 of 16 December 2013 [1] Chapter II, Article 5)
    - Test type I requirements: tailpipe emissions after cold start (Commission delegated EU Regulation No 134/2014 of 16 December 2013 [1] Chapter II, Article 6) and (Commission delegated EU Regulation No 134/2014 of 16 December 2013 [1] Chapter II, ANNEX II)

The type approval regarding environmental performance in running condition is based on chassis dynamometer tests of the full vehicle. No on-road tests with emission measurement are required.

3.1 Abstract of the EU Regulation No 134/2014

In the following major parts of the regulation are noted with respect to the recommendations for modification. For better understanding, the parts are described with their content, not the exact regulation text.

3.1.1 Regulated emission components

Exhaust gas emission components to be measured are subject to a limit in mass per distance g/km or mg/km, weighted for the different test phases and averaged over the specific test. The following components are subject to limitations:

- Hydrocarbons (HC)
- Carbon Monoxide (CO)
- Nitrogen Oxide (NO_x)
- Particulate Matter (PM)
- Carbon Dioxide (CO_2)

While HC, CO, NO_x, and PM are limited, CO_2 is recorded only for reference reasons. The current limits for EURO 5 are listed in Table 5.

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The Particulate Matter PM limit is only valid for Compression Ignition CI engines as well as Positive Ignition PI[13] Engines equipped with Direct Injection Technology. PI engines using Port Injection are not subject to the limitation.

Table 5: Emission limits EURO 5

		CO [mg/km]	THC [mg/km]	NMHC [mg/km]	NOx [mg/km]	PM [mg/km]
L1e-A		500	100	68	60	4,5[14]
L1e-B – L7e	PI/ PI Hybrid	1000	100	68	60	4,5[14]
	CI / CI Hybrid	500	100	68	90	4,5

3.1.2 Reference fuels [8]

Liquid reference fuels for the tests are specified as Petrol E5 (5% Ethanol content) and Ethanol E85 (85% Ethanol content) as well as Diesel fuel B5 (5% FAME).

3.1.3 L-category vehicle sub-classification for environmental testing [9]

The test I driving cycle type and test procedure (repetition of the WMTC test) is not regulated according the L-categories but with vehicle sub-categories based on engine capacity and maximum design speed. The assignment of the different test types and test procedures with boundary conditions refers to this classification. In Figure 25 a graphical description of the test cycles is given, in Table 6 the categorization is shown.

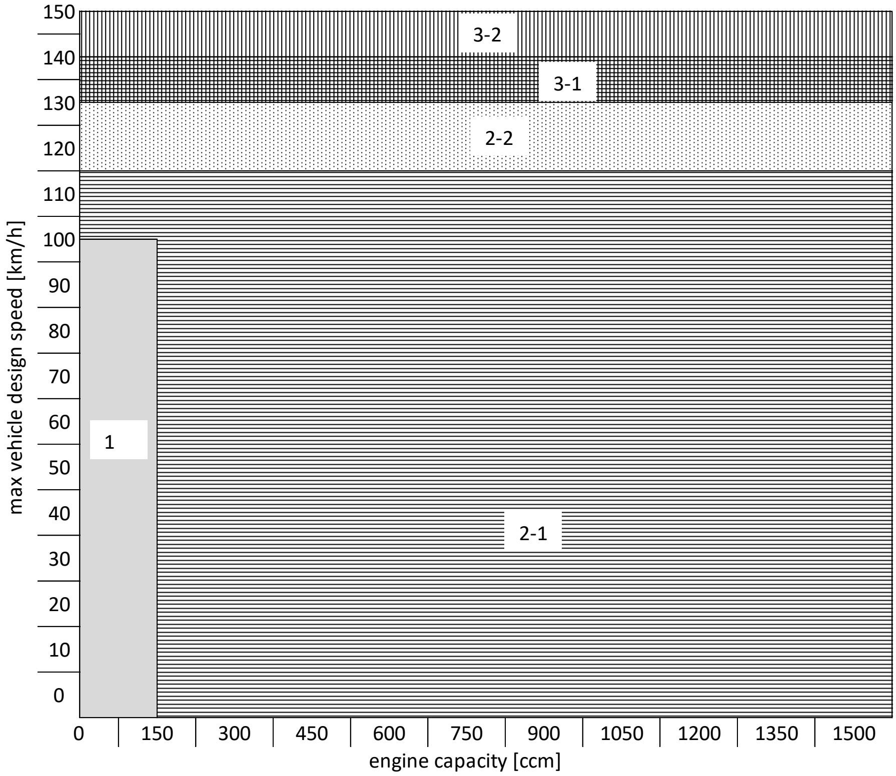

Figure 25: Test cycles related to vehicle max speed and engine capacity [5 ANNEX II, Figure 1-1]

[13] PI means positive ignition engines working according to the "Otto" cycle (mostly spark ignition petrol engines)
[14] Applicable to petrol direct injection (DI) engines only.

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Table 6: Specifications for sub-Class definition

Class	Engine capacity [cm³]	Design Speed v_{max} [km/h]
1	< 150	<100
2-1	< 150	$100 \leq v_{max} < 115$
2-1	≥ 150	< 115
2-2		$115 \leq v_{max} < 130$
3-1		$130 \leq v_{max} < 140$
3-2		≥ 140
3-2	> 1500	

3.1.4 Definition of the driving cycles for type I “exhaust emissions after cold start” test [10]

The WMTC[15] test cycle (vehicle speed patterns) for type I environmental test consists of up to three parts and is defined as a vehicle velocity trace over time ([1] Appendix VI). WMTC test cycle parts are shown in Table 7.

Table 7: WMTC test cycle parts for class 1.2 and 3 L-category vehicles ([5] ANNEX II, Table 1-4)

L-category vehicle (sub-)class	Applicable parts of the WMTC as specified in Appendix 6
Class 1:	Part 1, reduced vehicle speed in cold condition, followed by part 1, reduced vehicle speed in warm condition.
Class 2 subdivided in:	
Sub-class 2-1:	Part 1, reduced vehicle speed in cold condition, followed by part 2, reduced vehicle speed in warm condition.
Sub-class 2-2:	Part 1, in cold condition, followed by part 2, in warm condition.
Class 3 subdivided in:	
Sub-class 3-1:	Part 1, in cold condition, followed by part 2, in warm condition, followed by part 3, reduced vehicle speed in warm condition.
Sub-class 3-2:	Part 1, in cold condition, followed by art 2, in warm condition, followed by part 3, in warm condition

3.1.5 Weighting of WMTC results

The emission collected in the different test cycle phases are averaged for each cycle part and weighted specifically for the L-category[11].

3.1.6 Gear shift procedure for type I test[12]

For manual gear vehicles the gear shifting in type I tests is defined as gear setting (gear 1, 2, 3, …) over time for each time step of the test. This gear setting is based on a formula with normalized engine speed and delivers a fixed gear for each driving condition.

[15] WMTC World harmonized motorcycle test cycle

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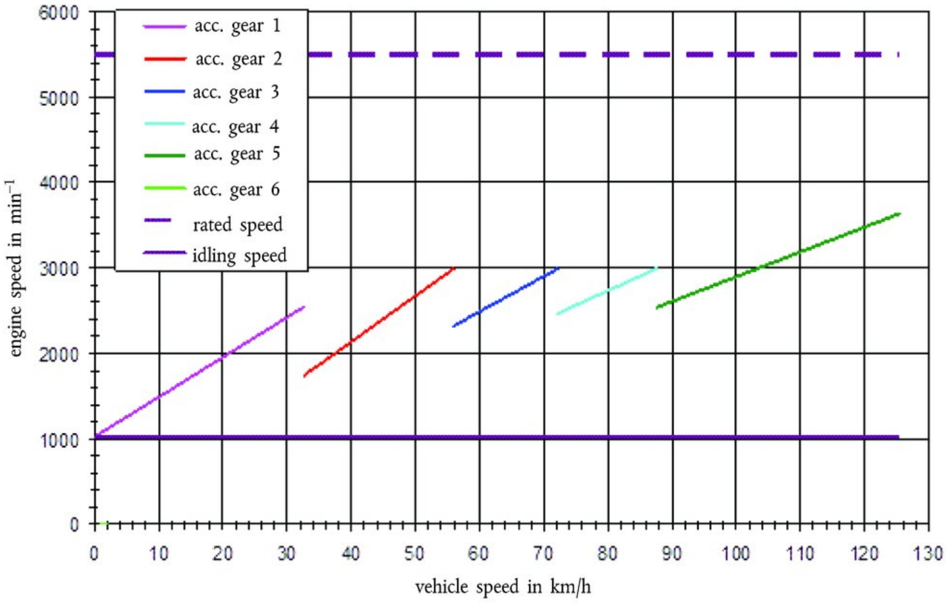

Figure 26: Example of a gearshift sketch — Gear use during acceleration phases [13]

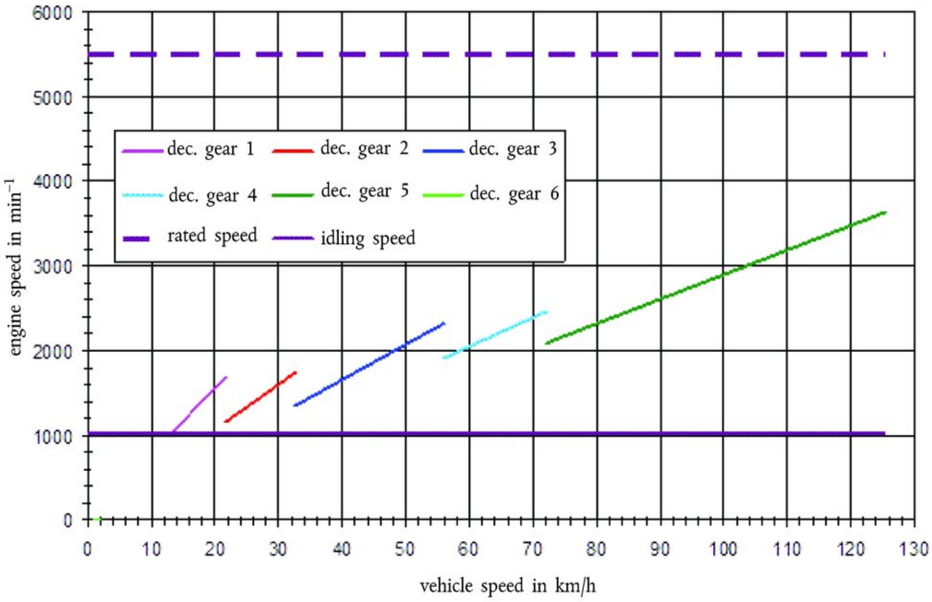

Figure 27: Example of a gearshift sketch — Gear use during deceleration and cruise phases [13]

3.1.7 Classification of equivalent inertia mass and running resistance[14]

The road load setting for the chassis dynamometer test for the different driving cycles are based on either on-road coast-down measurements or from a running resistance table. This table defines the equivalent inertia mass, the rolling resistance and the aero drag coefficient based on a reference mass regardless of particular L-category vehicle characteristics.

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4 Current Type Approval Regulations from other Vehicle categories

For reference and hints for potential improvements several key areas for emission regulation from other vehicle categories and emission regulations are described. The most important area is the regulation for real drive emission measurement which is in force for LDV and HDV. Regulations from other regions of the world like EPA or China include measures to reduce tailpipe emission which can be transferred to the L-category TA regulation suggestions. In these regulations measures regarding emission components not considered in EURO 5 and real-world measurements are contained. In particular, these regulations are:

- EPA Environmental Protection Agency USA[15]
- CARB California Air Resource Board[16]
- JAPAN
- China
- India
- South Korea K-LEV

4.1 Regulations

This section contains a summary of the state-of-the-art in requirements of regulations related to exhaust emissions covering other vehicle categories. Some of the actual Euro5+ non-regulated pollutants for L-category vehicles are considered by other regulations, other regions, and other vehicle categories.

The most usually regulated components for gasoline LDV are included in the following table which cover all regulations worldwide.

Table 8: Regulation for gasoline LDV in different regions of the world

	Euro 6d	Euro 7	EPA Tier 3	CARB LEV IV	JAPAN	Brazil P8	China 6b	India Bharat VI	South Korea K-LEV III
PM	YES 1)	YES	YES	YES	YES 1)	YES 1)	YES	YES 1)	YES
PN	YES 1)	YES					YES	YES 1)	
NMOG			YES	YES		YES			YES
HCHO			YES	YES		YES 2)			
NH3									
N2O							YES		

1) Only regulated for direct injection
2) Only regulated for Otto-cycle motors

For diesel vehicles, the requirements slightly differ, and are included below:

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Table 9: Regulation for diesel LDV in different regions of the world

	Euro 6d	Euro 7	EPA Tier 3	CARB LEV IV	JAPAN	Brazil P8	China 6b	India Bharat VI	South Korea K-LEV III
PM	YES	YES	YES	YES	YES	YES	YES	YES	YES
PN	YES	YES					YES	YES	YES
NMOG			YES	YES		YES			
HCHO			YES	YES					
NH3						YES [1)]			
N2O							YES		

1) Only diesel engines with SCR using urea.

And last, but not least, in other areas of the world, motorcycle regulations sometimes consider (for various reasons) limitations for other components.

Table 10: Regulation additional emission components for motorcycles in different regions of the world

	EPA Tier 2	CARB LEV III	Brazil P5	China 4	India BS VI	K-MOT 2019
PM			YES	YES [2)]	YES [1)]	
HCHO			YES			

1) Only regulated for direct injection and compression ignition engines
2) Only regulated for 3 wheelers with compression ignition engines

It is important to mention that particulate matter is regulated in Euro 5+ for L-Category vehicles but only limited for compression ignition engines.

Procedures can be modified for every area, and sometimes they differ from country to country. An example of this is the EPA regulation, in which things like soak time (depending on engine capacity) and driving trace (different speed trace and a hot soak during the test) are different from the European Regulations.

A more detailed explanation of regulated pollutant in Euro 5+ is included in the following bullet points:

- **NMOG:** Measurement performed in EPA Tier 3, CARB LEV IV, Brazil P8 and K-LEV III (gasoline). NMOG is the sum of all organic pollutant gases excluding methane. This includes aldehydes, acetones, alcohols and other contaminants that are precursors of ozone which produce vegetation degradation, reduced photosynthesis, and compromised crop yields. Ground-level ozone formation, driven by nitrogen oxides and organic compounds, creates persistent photochemical smog that severely deteriorates air quality in urban areas. Moreover, these contaminants trigger significant health risks, including respiratory complications, lung inflammation, and increased vulnerability to cardiovascular diseases.
- **HCHO (Formaldehyde):** Measurement performed in EPA Tier 3, CARB LEV IV and Brazil P8 (regulated for Otto-cycle motors). This contaminant plays a pivotal role in atmospheric chemistry by serving as a key precursor to ground-level ozone formation and photochemical smog generation. The environmental severity of HCHO is substantial, dramatically impacting urban air quality through its ability to initiate complex chemical reactions that produce secondary pollutants, thereby intensifying atmospheric degradation. Its high reactivity contributes to reduce atmospheric oxygen quality, increase respiratory irritants, and persistent ecological disruption. The complexity of HCHO's environmental interaction underscores the urgent need for comprehensive technological and regulatory approaches to address its widespread atmospheric and ecological implications.
- **PN:** Measurement of the total number of non-volatile particles performed in Euro 6d, China 6b, India Bharat VI and South Korea LEV III. Compared to PM, which is a metric of total particulate mass, PN represents a total count of particles, including nanoparticles. This provides more comprehensive pollution assessment as well as indicating potential health and environmental risks. PN emissions pose

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a critical health threat through ultra-fine particles that can penetrate deep into human respiratory and cardiovascular systems, crossing biological barriers with ease. These microscopic (nano-) particles can infiltrate lung alveoli, enter bloodstream circulation, and potentially reach critical organs, triggering systemic inflammatory responses. The primary health risks include increased respiratory and cardiovascular diseases, potential genetic alterations, and compromised immune system functions. Prolonged exposure correlates with accelerated aging, higher cardiovascular disease probability, and potential neurological disorders.

- **NH_3 (ammonia):** Measurements are performed in Brazil P8 (diesel engines with urea). Ammonia (NH_3) contributes to atmospheric nitrogen deposition, causes soil and water ecosystem acidification, triggers eutrophication in aquatic environments and disrupts natural nutrient balance in ecosystems.

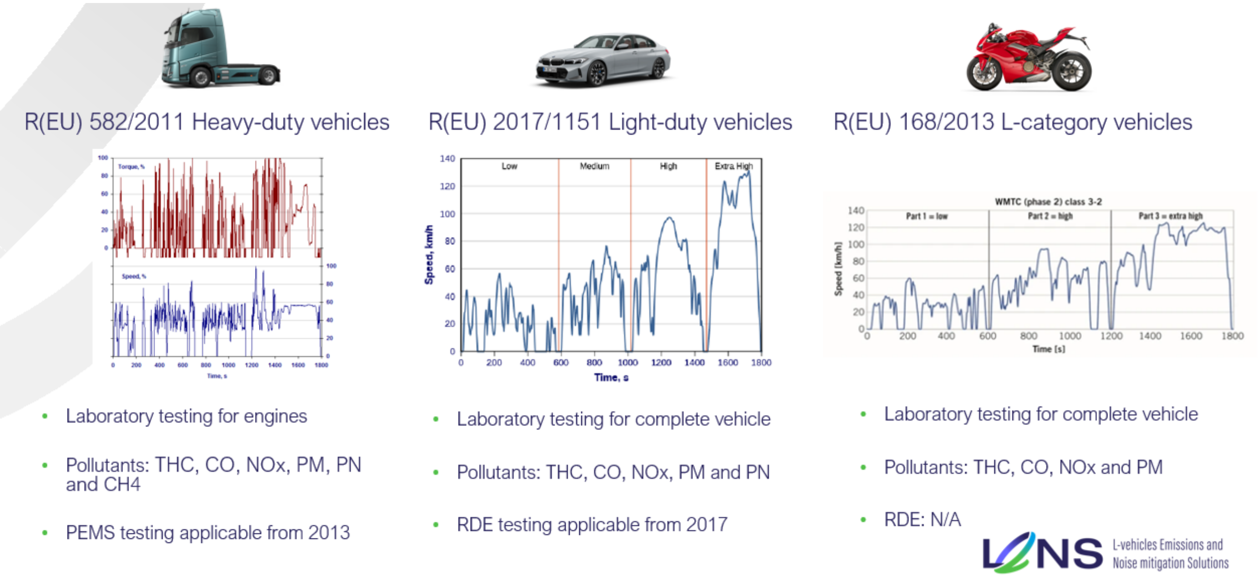

Figure 28: Major EU emission regulations[16]

In European standards, heavy-duty vehicles R(EU) 582/20211 incorporates PEMS testing from 2013. First testing on-road for emissions type-approval for vehicles were required. The pollutant emissions required for HD vehicles are THC, CO, NOx, PM, PN and CH4 and are measured in engine bench at a component level. Light-duty vehicles R(EU)2017/1151 require testing at a vehicle level in chassis dynamometer and the pollutant emissions required are THC, CO, NOx, PM and PN. RDE testing is applicable for 2017 and onwards. The picture for LVs shows there is room for improvement in the requirements demand for this kind of vehicles. Testing is also done on chassis dynamometer, emission components required are THC, CO, NOx and PM, whereas RDE is not required. In the following chapters recommendations to improve LVs type-approval requirements are explained and the basis for discussion is the state-of-the-art also in the requirements level for other vehicle categories and other regions of the world.

4.2 EU Light Duty Vehicle Regulation

4.2.1 Chassis dynamometer parameters for running resistance

The table values for chassis dynamometer setting as presented in Appendix 5 to emissions type-approval EU Regulation No 134/2014 do not correspond to those in place for the emissions type-approval of passenger cars in EU Regulation No 2017/1151. For passenger cars, these values are not chassis dynamometer settings, but

[16] PM L-category CI only

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target settings. This means that the chassis dynamometer should be set such that the running resistance replicates the resistance as specified by the table values, thereby making the table values directly comparable to the measured running resistance by the coast-down test procedure. More importantly, the effect of the parasitic losses and tyre rolling resistance on the chassis dynamometer is implicitly compensated, making results from different dynamometers better comparable. Furthermore, the coast-down procedure for passenger car has a number of other aspects that improve the procedure, such as the introduction of a f_1 fitting parameter, smaller speed intervals and corrections for wind.

4.2.2 Regulatory Status of NH_3 in LDVs

Currently, ammonia measurement is technically required or strongly recommended under various legislative frameworks but is not yet subject to binding emission limits for light-duty vehicles (LDVs).

Table 11: Status of NH3 limitations in different regulations

Regulatory Framework	**NH_3 Status**
UN/ECE Regulation No. 83	NH_3 measurement optional; no limits
EU Regulation 2017/1151	NH_3 recommended for development and monitoring
GTR No. 15 (Annex 7)	NH_3 measurement defined, but without mandatory limit values

Thus, NH_3 is currently measured in certified test labs as part of development and validation procedures, but no binding compliance thresholds apply yet for LDVs.

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5 Suggested modifications to TA procedure EURO5

5.1 Introduction / Weaknesses of the current TA method

The current tailpipe emission regulation EURO 5 focuses on limits for selected emission components which are measured in a specified laboratory-based test program. The purpose of the type approval tests according to this regulation is to reduce the tailpipe emission of motorized vehicles of the category L to a level, which is expected to be not harmful to the environment. From the measurements of 150 vehicles, described in deliverable D3.4 "Pollutants and noise emissions in the real world" and D4.2 "Exhaust emission data from laboratory tests", the following findings can be drawn:

1. As described in chapter 2 "Summary and conclusions of exhaust emission related measurements" it was found, that the real-world emission level is considerably higher than the emission limit of EURO 5, although in the majority of cases the emission limit, pertaining to the type approval procedure, was fulfilled on WMTC cycles (see chapter 5.2).
2. The measurements showed that compared to the emission regulation of LDV[17] the number and mass of particulate matter is considerable for the tested types of vehicles. In the current emission regulation of L-category vehicles the particulate emission is regulated for compression ignition (CI) engines and spark ignition (SI) engines with direct injection only. As all of the tested vehicles had SI engines with external mixture preparation, this regulation is not applicable to any of the vehicles tested, neither it is applicable to the majority of L-category vehicles on the road.
3. The current emission regulation limits the emission components carbon monoxide CO, total hydro-carbos THC, non-methane hydrocarbons NMHC and the sum of nitric oxide and nitrogen dioxide (NO_X). From the measurements it was found that several other non-regulated emission components reach a considerably high level (Deliverable 3.4).
4. In the current regulation, there is no limit for fuel and/or electric energy consumption and electric range; CO_2 emissions are, however, measured and reported. In some countries in Europe a CO_2 based tax is in force.
5. Out of the high emission event analysis performed until now, several events with high contribution to emission could be identified:
    - Cold start conditions were found to be a major contributor to elevated NO_x emissions. On average, cold start events resulted in approximately 8.8 times higher NO_x emissions than the average emissions over the full trip duration. This confirms that cold engine operation significantly increases pollutant output, likely due to suboptimal combustion and inactive after-treatment systems during engine warm-up. Although, NOx emissions during cold start are not representative at all, as overall NOx emissions are not problematic. CO and HC emissions are highly sensitive to those cold start situations, reaching +10 times HC, +20 times CO on average over the full trip duration of WMTC (unweighted value).
    - "Acceleration from stand-still" events were successfully identified using velocity profiles and were characterized by distinct acceleration phases beginning from near-zero speed. Emission in [g/kg CO_2] from these events showed modest increase, in some cases even a slight reduction.
    - Comparative Emission behavior: HC and CO emissions demonstrate similar patterns. Both pollutants emerge under typically the same conditions of high vehicle speed and high rpm, and when engine

[17] LDV Light Duty Vehicles

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operates with excess fuel (fuel-rich, lambda lower than stoichiometric). Hydrocarbons (HC) exhibit distinct emission characteristics, increasing under different operational parameters.

- CO emissions are often not controlled under high engine load and at high engine speed when engine runs fuel-rich. These operating points should be better covered on future regulations, as they can result on exceeding current limit values, especially on CVT vehicles that are commonly driven at high engine load, which trigger carbon monoxide emissions on a severe way. L3e-A1 vehicles are also prone to those critical situations in terms of emissions. 2-stroke engine are also prone to result in critical CO emissions.
- HC emissions show a similar pattern as CO but they are not as severe, since maximum values are not as high as CO ones and its low occurrence do not result in a problematic scenario. Same patterns as HC, but less sensitive to real-world driving conditions. HC emissions are triggered by two orders of magnitude less than CO ones. 2-stroke engine are also prone to result in critical CO emissions.
- NOx emissions are not a problem on the measurement considered in the current analysis. Inverse behaviour with respect to CO emissions under high engine load and/or high engine RPM because of the inverse response to low lambda (<1) values. Some engine configurations are more prone to NO_x emissions.

6. It was found that for the sub-categories L7 very few vehicles can be found in the fleet. The majority of these vehicles are type-approved in the tractor category with considerably different, and lower, demand on the emission behavior.

In the following, these findings are addressed and recommendations for type approval modifications are given for each topic.

5.2 Suggestions to cover the differences between real world emission and type approval tests

In chapter 2 the observed difference between the tail pipe emission in the engines operation area which is covered by the type approval test and outside of this area is remarkable and reaches ten times of the limit for some vehicles and sub-classes[18] . To reduce the emission outside of the WMTC engine operating conditions, several possibilities for type approval modifications are described in the following. These possibilities comprise modification of the type approval laboratory test cycles as well as emission testing in real-world environment.

5.2.1 Driving Cycle adaption for lab tests

Current test cycle for type approval is the revised WMTC test cycle in different stages. As shown in chapter 2.3 this test does not correspond to the real-world driving in terms of speed, acceleration, and engine operation area coverage. For an extension of the covered operation area of the engine, a modification of the test cycle is recommended. Several measures are possible.

5.2.1.1 Modified road load factors

The conclusions of the analysis of real-world running resistance (chapter 7 “ANNEX I Determination of real-world running resistance) lead to the following recommendations to make the running resistances on the chassis dynamometer match closer to the actual running resistance on the road:

- The table values in Appendix 5 to emissions type-approval EU Regulation No 134/2014 should be investigated to quantify the gap between chassis dynamometer setting from the coast-down test procedure and the tables values for a whole range of recent models of on-road motorbike types. On the

[18] Without tampered vehicles

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basis of the outcomes of that investigation the following recommendations should be taken into account:
    - The table values in Appendix 5 to emissions type-approval EU Regulation No 134/2014 for the chassis dynamometer setting should be revised to consider different aerodynamic characteristics of vehicles in the same mass class. This could be done by adding an aerodynamic related factor to the table.
- As these actual table values are direct setting parameters of the chassis dynamometer, not considering vehicle and chassis dynamometer specific running resistances (i.e. tire-roller contact), it is recommended to use the approach of the passenger car EU Regulation No 2017/1151. In this, the table values are target values for the rolling resistance on the chassis dyno which must be reached by repeated adaption of the chassis dynamometer set parameters in an iterative procedure. This will also make the emission results better comparable by reducing the influence of the specific chassis dynamometer. As a consequence, a new set of table values would have to be developed.
- To account for the (expected) aerodynamic characteristics of the vehicle, it is advised to consider that element in the table value scheme, although this is probably not easy to objectively include.
- The coast-down test procedure is recommended to be evaluated and improved, by taking in elements from the procedure for passenger cars in EU Regulation No 2017/1151 that are currently missing, such as a third fitting parameter for the running resistance curve, smaller speed intervals and applying a correction for the influence of wind.

5.2.1.2 No mandatory gear regulation

In the current regulation a definition for the gear change and gear setting is contained, based on normalized maximum and idle engine speed. This is due to repeatability reasons, but limits the representation of real-world driving behavior and therefore emission in laboratory measurements. A free shifting could improve this.

5.2.1.3 Adaption of WMTC cycles

In the current regulation, WMTC classes are defined primarily based on the vehicle's maximum design speed (v_{max}), with fixed phase combinations and speed limits assigned accordingly (see chapter 3). While this classification offers a straightforward framework for type approval, it does not sufficiently reflect the diverse range of motorcycle designs, performance levels, and, most importantly, real-world usage patterns.

As a result, certain vehicle types, especially those with high power output or aggressive riding profile, are significantly underrepresented in terms of dynamic and emissions-relevant driving conditions within the WMTC (see chapter 2.3). The following proposals aim to improve the representativeness and regulatory effectiveness of the test cycle.

Reclassification Based on Power-to-Weight Ratio (PWR)

To differentiate more effectively between vehicle behavior and emission characteristics, it is proposed to extend the current classification scheme by incorporating the power-to-weight ratio (PWR) as an additional parameter:

- Vehicles with the same v_{max} but vastly different PWR (e.g. an A2 scooter vs. a super-sport model) would be assigned to distinct test cycles or adjusted versions of WMTC.
- Thresholds could be defined analogously to motorcycle license categories (e.g. 0.2 kW/kg as a baseline) or introduced in finer bands.

This would allow tailoring the test procedure more precisely to the real driving dynamics and emission potential of different vehicle types.

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Enhancing Dynamic Load in WMTC Cycles

To improve the correlation between type-approval and real-world emissions, the following changes to WMTC are recommended:

- Increased Maximum Speed:
  For motorcycles intended for highway use (e.g. L3e-A3), the maximum speeds within WMTC cycles should be raised—potentially up to 130–140 km/h—where applicable.
- Higher Acceleration Rates:
  Real-world data shows that current WMTC acceleration patterns are too mild. Many vehicles regularly exceed acceleration levels of 2.0 m/s^2 in normal use, which is not captured in the existing test profiles (chapter 2.3). The feasibility of higher accelerations on two-wheeler chassis dynamometer has to be checked, however. These driving dynamics, which have been carefully analysed in D3.5 have shown that the coverage of WMTC is very close to what we have on PC's WLTC, whereas standard RDE differs considerably between L-category vehicles and PCs, especially for L3e-A2 and L3e-A3 subcategories.
- Increased Engine Speed Usage
  Operational engine speed ranges in the real world often exceed 70 % of the nominal speed for significant periods, much more than what is currently reflected in WMTC. Test cycles should be extended to include these high-RPM conditions.
- Integration of Load Transitions and Full-Load Events
  Current cycles contain few rapid load changes and almost no full-load scenarios, which are critical for assessing emissions spikes (especially CO and PN). A more aggressive load profile should be included, which goes in hand with higher acceleration rates mentioned previously.

Inclusion of high emission events

- Cold start events should be included in the testing framework in a representative way, as they are known to produce elevated emission levels during the engine warm-up phase. These events can be clearly defined either by monitoring engine coolant temperature or by applying a fixed time window after engine start. In the current framework only one cold start is mandatory, it should be verified if the share of driving with a cold engine is representative for real-world driving.
- Additionally, acceleration from standstill should be included in the text in a representative way. This is particularly important under both loaded and unloaded scenarios, as it reflects the frequent stop-and-go nature of urban driving, which significantly influences emission. Additional investigations are recommended to define proper representation on the base of vehicle categories.

Application-Based Phase Weighting

Currently, the WMTC cycle definitions (low, medium, high speed) are combined in fixed proportions based on parameters like v_{max}, without considering real-world usage profiles. This uniformity leads to unrepresentative emissions results for different vehicle types. To address this, we propose an application-profile-based phase weighting, tailored to typical usage patterns of various vehicle categories. Examples for such usage patterns are shown in Table 12, an appropriate weighting must be defined.

Table 12: WMTC phase weighting using application profile

Vehicle Category	Typical Use Case	Environment
L1e (mopeds)	Low-speed, short-distance commuting	Urban / Suburban
L2e (3-wheel mopeds)	Like L1e, low performance	Urban / Suburban
L3e-A1 (scooter)	Light scooters (<98 km/h), commuting	Urban / Suburban
L3e-A1 (naked/supermoto)	Lightweight motorcycles with broader range	Urban / Rural

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Vehicle Category	Typical Use Case	Environment
L3e-A2 (scooter)	Medium-performance commuting scooters	Urban / Rural
L3e-A2/A3 (touring, naked, chopper)	General-purpose, often mixed-use	Urban / Rural / Highway
L3e-A3 (super-sport)	High-performance sport motorcycles	Rural / Highway / Dynamic use
L3e-AxE (enduro)	Dual-purpose, mainly rural and off-road	Rural / Light Urban
L4e (sidecar motorcycles)	Mixed-purpose with stability demands	Urban / Rural
L5e (trikes)	Large, touring-style 3-wheelers	Urban / Rural / Highway
L6e (light quadricycles)	Restricted-speed vehicles	Urban only
L7e (heavy quadricycles)	Sporty or utility quads and SSVs	Rural / Utility / Some Urban

For the definition of the application profiles vehicle specific specifications must be found. These could be:

- specification of long-rang (touring) or short-range operation profile by the maximum trip distance with fuel tank volume, based on WMTC trips
- maximum power
- maximum design speed
- power-to-weight ratio
- engine capacity

5.2.1.4 Real Drive cycles

To improve the lab test procedure instead of using the WMTC test cycles only, synthetic test cycles (RDC) from recorded RDE events can be used. Examples can be found in Hiesmayr, et al [[17]]. These cycles should be L-category specific or at least specific to the rated power and / or maximum design speed of the vehicles. They are not vehicle brand & model specific and can be randomly generated out of a database of segments of recorded RDE cycles of each L-category. Several trips for each category must be recorded and a procedure for merging the segments to one RDC trip must be provided. A classification of the RDC test cycles according to the existing definition of WMTC cycles can be used. For the boundary conditions the suggestions of chapter 5.2.1.3 should also applied to the RDC cycles.

Nevertheless, some mismatch between on-road driving and RDC cycles will remain, as especially for high powered L-category vehicles the higher acceleration rates driven on the road cannot be reproduced on a chassis dynamometer.

5.2.2 On-Road Real Drive Emission RDE

To remove the possibility of drive cycle adaption of the powertrain control to cope with the regulation and to extend the covered operation area of the vehicle during the test to the maximum possible, emission tests with real-world driving can be considered. These so called RDE tests are in force for other vehicle categories like LDV and HDV as well as in other regions in the world. Two types of RDE test can be categorized:

1. full RDE measurements collecting all regulated emission components and driven in various scenarios on-road in real world conditions, and
2. reduced RDE tests were only selected emission components or only trip and engine operation data are collected during the measurement trips on-road.

The latter option gives the possibility to combine RDE and Lab tests. If not all required emission components can be measured on-road, additional tests in laboratory have to be performed using RDC cycles.

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5.2.2.1 Full RDE tests

Full RDE tests are standard for other vehicle categories and the test procedure can be derived from these regulations (LDV EURO 7 [3]). The benefits of these full RDE tests are that they cover potentially the whole engine operation map and force non-foreseeable driving situations. The measured emission levels are close to the real-world emissions of the fleet. However, as vehicles of the L-category differ considerably from the vehicles of M-category of N-category, some difficulties occur for these measurements.

- Current available measurement equipment is not suitable for all L-category sub-categories due to weight and size restrictions
- Not all emission components can be measured safely with the current equipment on motorcycles, i.e. hydrocarbons as the valid HC measurement method FID uses burn gas which is not safe to transport on a two-wheeler.

From the experience with on-road measurements it can be concluded that the smaller L-category vehicles like L1e-B, L6e-A and L6e-B are not possible to equip with today`s type approval grade PEMS , the category L3e-A1 is difficult to equip (see also Table 16). For all other categories a RDE test equivalent to the required tests for M-category vehicles is recommended. However, not all emission components can be measured on L-category vehicles, especially two-wheelers. Additionally, due to the very dynamic driving behaviour of L-category vehicles special care must be taken regarding the boundary conditions and requirements for RDE trips (chapter 5.2.2.3). Considering these points, it is recommended that RDE test are a mandatory but additional test to the laboratory tests.

5.2.2.2 Reduced RDE tests

As for some L-categories full RDE measurements are not possible due to weight, space and other restrictions, a reduced RDE test approach can be followed. Typically, this occurs with smaller vehicles like the L3e-A1 and L1e-B two-wheeler. Driving these vehicles equipped with a GPS sensor and connected to the OBD CAN-Bus in a standard RDE test trip like 5.2.2.1, the speed vs time signal can be recorded together with major engine and propulsion parameters like engine speed, gear, throttle position. Every type approval requires a dedicated RDE trip with exactly the type approval vehicle. For these lower powered vehicles classes, a reproduction of the recorded RDE trip on the chassis dynamometer is possible. A free gear shift has to be allowed, so the recorded OBD data cannot be used as reference for the validity. Instead, the measurement of one emission component like NO_x on-board and in lab can be used as comparison.

5.2.2.3 Boundary conditions / RDE trip requirements/KPIs

Based on the analysis of driving dynamics (Deliverable 3.5) it is obvious that the real world driving dynamic values like $v*a_{pos}$ or relative positive acceleration RPA is considerably higher than for passenger cars. For RDE trips with L-category vehicles measures to ensure that the driving dynamic is appropriate must be taken. Appropriate means not considerably lower or higher than the average driving dynamics of the addressed category. In the LDV regulation EURO 6d temp for passenger cars, RDE trip requirements focusing on driving dynamics were introduced and are contained in EURO 7 [3] regulation also. A takeover of general RDE trip requirements from EURO 7 passenger car proposal is advised, but specific conditions for L-category vehicles must be considered.

The following aspects should be addressed for RDE trip boundary conditions:

- Weight of measurement equipment must be considered as in contrast to passenger cars the weight has a high share of the total mass in running order.
- Inclusion of high emission events

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- Cold start events should be included in the testing framework in a representative way, as they are known to produce elevated emission levels during the engine warm-up phase. These events can be clearly defined either by monitoring engine coolant temperature or by applying a fixed time window after engine start. In the current framework only one cold start is mandatory, additional cold-start events or events after longer stand-still periods could improve the compliance of the type approval tests with the real-world driving.
- Additionally, acceleration from standstill should be incorporated as a standard test condition. This is particularly important under both loaded and unloaded scenarios, as it reflects the frequent stop-and-go nature of urban driving, which significantly influences emission profiles.

- Environmental aspects play a considerable bigger role in L-category vehicle tests on-road as for passenger cars, as these vehicles cannot be easily and safe tested in rainy or winter condition. Therefore, a restriction of certain environmental conditions is necessary.
- Driving dynamics: In-operation control of the non-exceedance of the driving dynamic parameters is difficult to ensure on L-category vehicles, which would lead to a high number of invalid tests if a 1 to 1 take-over of the EURO 7 passenger car regulation[18] concerning these parts is done. As there is a necessity to control the driving behaviour and dynamics of the L-category vehicles, appropriate measures have to be introduced. To better understand how these driving dynamics behave across LENS measurements, a more detailed analysis was performed in D3.5, where evidence of how PMR and engine performance affect the dynamics of each subcategory is presented. Studies for feasibility of driving dynamic parameter control and limits must be performed in order to give specific recommendations on this topic.

5.3 Inclusion of additional emission components:

From the measurement data it can be observed that several emission components are noticeable high compared with current regulations from other vehicle categories (see chapter 2). Some of these are not considered in the current TA regulation for L-Cat vehicles and should be targeted in future regulations.

5.3.1 Particulate number

As outlined in the chapter on current emission levels, measurements conducted using the WMTC reveal substantial differences in solid particle number emissions (SPN10) across L-category vehicle types. Particularly, vehicles in the L1e-B category (mopeds) show significantly higher PN emissions compared to other two-wheelers, which can be attributed both to their technological design and to the lack of regulatory requirements to date.

While the passenger car (M-category) sector has implemented a particle number limit (6×10^{11} #/km for SPN23) since Euro 5b in 2011 [[19]], no such limit currently exists for L-category vehicles. This regulatory gap allows especially low-cost and technically simple L-vehicles to continue emitting large quantities of ultrafine particles - raising public health concerns.

5.3.1.1 Technological and Regulatory Differences Compared to Passenger Cars

The differences between L-category and M-category vehicles concern both technical configurations and the legal framework:

- Powertrain and exhaust system architecture: While passenger cars rely on modern direct injection engines with full exhaust aftertreatment systems, L-vehicles are predominantly equipped with naturally aspirated engines and basic aftertreatment systems utilizing TWCs as countermeasures for gaseous pollutions only.

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- Type approval procedures: In the passenger car sector, PN measurement is an integral part of the type approval process under Euro 6, using well-established measurement protocols, defined limit values, standardized test conditions, and calibrated measurement systems.
- Particle cut-off size (D50): The current PN limits for passenger cars refer to particles with diameters above 23 nm (SPN23). However, L-vehicles - especially high-revving motorcycles with port fuel injection (PFI) and short exhaust systems - emit particles with much smaller diameters (median ~25 nm or lower), making SPN23 less suitable for capturing the real emissions of these vehicles. This underlines the importance of shifting toward SPN10 measurements as already outlined in the EU7 proposal for LDVs.

5.3.1.2 Integration into the Type Approval Procedure – Methodological Considerations

A stepwise introduction of a particle number limit for L-category vehicles is environmentally necessary considering the high PN numbers of L-category vehicles and comparable regulations for passenger cars. The technical feasibility of the measurement instruments is documented in chapter 5.6.2.1. Key aspects include:

1. Measurement Methodology and Definitions
   Particle cut-off diameter (D50): In the passenger car sector, PN measurement is currently based on a D50 of 23 nm (SPN23). For L-category vehicles - particularly motorcycles with PFI concepts, very short exhaust paths, and rapid dilution and cooling - the dominant particle sizes are often smaller. Studies [20] report median sizes around or below 25 nm. As a result, SPN23 fails to capture a large portion of the actual emissions.
   A shift to SPN10 (D50 = 10 nm) is therefore recommended for L-category vehicles. This better reflects real-world emissions, especially under typical operating conditions such as cold starts, transient accelerations, and brief rich mixture phases. These conditions often generate short-lived but intense peaks of ultrafine particle emissions, cumulating to significant cycle emissions.
2. Requirements for measurement equipment:
   The high dynamics of particle concentrations in L-category vehicles - characterized by large ratios between baseline and peak emissions - require high-resolution measurement instruments with accurate dilution control and validated D50 performance.
3. Limit Values and Implementation Strategy
   Alignment with passenger car limits: A limit value equivalent to that for passenger cars (6×10^{11} #/km) could serve as a reference - adjusted where necessary to account for typical L-category use cases and powertrains.
   Phased implementation: Initially applying the PN limit to technologically advanced categories (e.g., L3e motorcycles) allows the industry to adapt. Gradual expansion to other categories (L1e-B, L6e, L7e) can follow, with appropriate lead times.
4. Integration into Existing Type Approval Legislation
   Introducing a PN limit would require an amendment to Annex II of EU Regulation No 168/2013, including "particle number (SPN10)" as a regulated pollutant for L1e to L7e vehicles. This would be supported by updates to relevant delegated regulations, particularly EU Regulation No 134/2014, specifying test procedures, instrumentation, limit values, and calibration requirements. The methodology should align with UNECE GTR 15 (Global Technical Regulation for light-duty emissions) to ensure international harmonization and data comparability. Considering, that the mixture preparation technology of existing and current L-category vehicles is port fuel injection, the regulation should address not only direct injection SI and CI engines but all types.

5.3.1.3 Advantages of Integration via Type Approval

Regulatory coherence: Harmonizing L-category requirements with those of M-category vehicles improves transparency, consistency, and credibility in EU emissions policy.

Technological stimulus: Including PN in type approval incentivizes the development of cleaner combustion and emission control technologies - without prescribing a specific technical solution.

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Improved public trust: Extending particle number regulation to L-vehicles enhances the perception of comprehensive emission control policies, particularly with regard to ultrafine particles and their known health effects.

5.3.2 Particulate mass

In contrast to particle number emissions, particulate mass emissions (PM) are currently regulated only for L-category vehicles equipped with compression ignition (CI) or positive ignition (PI) direct injection (DI) engines. Although the measurements (2.2.4) show, that many of the tested vehicles are within the EURO 5 PM limits, several vehicles with positive ignition port injection engines, which are not subject to the PM limit, exceed the limit value by a factor of 4.Therefore, an extension of the PM regulation for all type of engines is recommended.

5.3.3 Non-Exhaust Emissions

Non-exhaust particle emissions, such as those originating from brake wear, tire abrasion, and mechanical components, were not covered in the scope of this study. Nevertheless, the consortium recommends initiating targeted investigations for L-category vehicles, as these sources could represent a non-negligible share of total particulate emissions in real-world use.

In particular, L-category vehicles may exhibit elevated non-exhaust emissions due to their often exposed and unshielded secondary drive systems (e.g. chains or belts). These components are subject to environmental wear, lack of encapsulation, and mechanical losses that can lead to the release of metal, rubber, or lubricant particles into the environment. Given the increasing regulatory interest in non-exhaust sources - especially in the context of Euro 7 and forthcoming UNECE regulations - the consortium sees value in further research, with the long-term aim of assessing the necessity and feasibility of introducing regulatory limits or design guidelines for these emission sources in L-category vehicles.

5.3.4 CO_2 limits

Unlike M1 passenger cars, for which CO_2 fleet targets are defined under EU Regulation No 2019/631, L-category vehicles are not currently subject to mandatory CO_2 limits in the EU. Nevertheless, CO_2 emissions are routinely determined during type approval via the WMTC test procedure, providing a technical basis for evaluating energy efficiency and climate impact. Other countries like China or Taiwan have set standards for fuel consumption[19].

From the consortium's perspective, introducing CO_2 limits for L-category vehicles is not an immediate regulatory priority, but may be worth considering as part of a longer-term strategy for aligning all vehicle types with climate goals. A number of arguments support a differentiated and staged approach to CO_2 regulation for this segment.

On the one hand, L-vehicles offer the potential for efficient, low-emission urban mobility, and certain subsegments (e.g. urban scooters, light motorcycles) could contribute meaningfully to reducing transport-related CO_2 emissions. In this context, regulatory signals toward energy efficiency could drive the development of low-consumption internal combustion engines, the use of hybrid or electric drivetrains, and lightweight design.

On the other hand, the high diversity of the L-category - ranging from low-speed mopeds to high-performance motorcycles - poses a significant challenge for the definition of meaningful and fair CO_2 limit values. Additionally, many manufacturers in this segment are small-volume producers with limited capacity to manage complex regulatory compliance schemes. For cost-sensitive vehicle classes, especially mopeds and entry-level

[19] https://www.transportpolicy.net/standard/china-motorcycles-fuel-consumption/ accessed 2025.07.17

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motorcycles, additional regulation could disproportionately increase production and certification costs without delivering commensurate climate benefits.

Given these considerations, the consortium proposes the following approach:

- Systematic documentation and publication of CO_2 emissions as already determined during type approval. This data should be made accessible (e.g. via EU databases or vehicle labeling) to enable transparency and comparability for consumers.
- Voluntary or mandatory CO_2 labelling, similar to existing energy efficiency classes in other sectors, could serve as a market-based incentive for manufacturers and provide guidance for environmentally conscious buyers.
- Exploration of CO_2 fleet targets for large manufacturers (>10,000 units per year), with a differentiated structure according to power classes or vehicle categories (e.g. <11 kW, 11–35 kW, >35 kW). This would allow gradual integration of L-vehicles into overarching climate policy frameworks while considering their technical and economic characteristics.

In conclusion, while a binding CO_2 limit is not currently required for L-category vehicles, the use of CO_2 data as an evaluative tool can contribute to climate transparency and future policy alignment. A phased, data-driven approach - starting with improved visibility and voluntary schemes - could prepare the sector for future integration into EU climate legislation.

5.4 Category definition

In the course of the procurement of the 150-vehicle fleet, the observation was made that some vehicle categories could not be identified in the fleet (Deliverable 3.5 and Deliverable 4.2). The reasons are diverse: particularly in very small vehicles, L1 and L2 categories, combustion engines are increasingly replaced by electric power trains, for some categories type approval procedures with less stringent requirements are available. In the following, the L7e-B category is described.

5.4.1 L7e-B Heavy All-Terrain Quad

Despite the lack of detailed information about registration data it can be observed, that a considerable number of Heavy All-Terrain Quads can be found in the actual fleet. Both All Terrain Quads and Side-by-Side Buggies are well represented, although the distribution over the EU regions is not uniform. Nevertheless, only a small number of L7e-B vehicles could be procured for testing (7 vehicles) and the procurement was more time-consuming than for other categories. The reason seems to be that a majority of these vehicles are registered in the tractor category (T-category) [21]. Main requirements for the L7e-B category are

a. a vehicle mass in running order of ≤ 450 kg for passenger transport[20]
b. maximum design vehicle speed ≤ 90km/h for All terrain quad L7e-B1
c. maximum continuous rated or net power ≤ 15kW for Side-by-Side Buggy

Several All-Terrain Quads L7e-B1 on the market exceed a.) and especially Side-by-Side Buggies L7e-B2 have considerably more power than 15kW. This leads to the circumstance, that these vehicles are type approved in the T-category according EU Regulation No 167/2013. Additionally, this regulation allows for the special purpose wheeled tractors (sub-categories T4.1 and T4.2) to be type approved by the EU Regulation No 167/2013 or to comply with national requirements [21]. Both possibilities for type approval under different regulations have considerably less stringent emission requirements which leads to vehicles on the road with high exhaust emission. Some of these Side-by-Side vehicles, type approved according to [1], are not equipped with an exhaust gas aftertreatment system, which demonstrates the lower emission requirements.

[20] 600kg for transport of goods

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Extending the current L-category definition sub-class L7e-B for higher mass in running order and higher maximum power would include these vehicles in the L-category regulation and reduce the emissions considerably.

5.5 Boundary Conditions

5.5.1 Reference Fuel

In the EU Regulation No 134/2014 [1] the reference fuel is specified. E10 is not allowed at the moment and no calculations for higher ethanol content are given, Considering the trend to a higher renewable share this seems to be necessary as it influences the emission level.

5.6 Measurement equipment for L-Category Type Approval

5.6.1 Measurement equipment for RDE tests

For LDV and HDV RDE tests are mandatory and therefore measurement equipment is available. Obviously, these instruments were not designed for use on L-Category vehicles and are therefore rather big and heavy. First investigations [[22], [23]] showed, that the available equipment is not suitable for all L-categories. In the project, detailed investigations for the suitability of commercially available and prototype-status measurement equipment were performed. In the following the findings and derived recommendations from these investigations are given.

5.6.1.1 Commercially Available PEMS

Portable Emissions Measurement Systems (PEMS) were originally developed for use in the automotive sector, particularly for passenger cars, light-duty and heavy-duty vehicles. As a result, most commercially available systems are characterized by considerable system mass and packaging volume, which can present significant challenges when applied to smaller and lighter L-category vehicles such as motorcycles.

Market Overview and Applicability to L-Category Vehicles

Major PEMS suppliers currently offer systems optimized for automotive applications, often with total system weights exceeding the limits of feasible integration on two- or three-wheeled vehicles. As such, these systems are generally not suitable for L-category use, particularly for the L1e and L3e-A1 subcategories.

Within this project, the lightest available certified PEMS on the market was selected for testing and application. This system, including mounting hardware, exhaust flow measurement (EFM), GPS, weather station, and battery units, has a total weight of approximately 50 kg. Its design emphasizes compactness and robustness, with features such as modular mounting and battery autonomy for typical RDE testing durations.

Practical Experience and Application

The PEMS was successfully deployed on a broad range of L-category vehicles during the project. It showed good applicability for larger subcategories, including L3e-A2, L3e-A3, and L5e–L7e vehicles. Application on L3e-A1 motorcycles was found to be conditionally feasible, depending on the specific vehicle configuration, available mounting points, and overall weight sensitivity.

Throughout the measurement campaign, the PEMS was repeatedly cross-validated against certified laboratory instrumentation, including CVS-based chassis dynamometer tests. Comparative data sets were generated across a variety of powertrains and driving profiles. The robustness of the system under real-world conditions, as well as the quality of its emissions output (g/s and #/s), were confirmed. The methodology and selected results were

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presented at international conferences (e.g., SAE Bangkok, NPC Zürich), further supporting the validity of the system for RDE studies on powered two-wheelers.

Vehicle Impact and Weight Considerations

Given the relatively high system mass, particular attention was paid to the influence of PEMS installation on vehicle dynamics and emissions. Using coast-down measurements and resistance simulations, the project quantified the impact of added weight and drag on road load and thus on emissions. These analyses allowed for the adjustment or interpretation of test results in light of modified test vehicle characteristics and informed the feasibility assessment of PEMS application across vehicle types.

Historical Perspective and Sectoral Parallel

The current limitations in applying PEMS to motorcycles and light L-category vehicles closely resemble the challenges that were faced during the early stages of PEMS introduction for passenger cars. At that time, the systems were similarly large, heavy, and technically complex, with limited suitability for routine deployment in real driving conditions. Only through successive iterations - targeting system miniaturization, integration, and standardization - did PEMS evolve into the compact, reliable, and regulation-compliant tools now widely used in type approval for light-duty vehicles.

A similar technological trajectory is likely for powered two-wheelers, where adapted and optimized systems, such as the one used in this project, mark a first practical step toward broader applicability. As legislative pressure and research demand increase, further developments in lightweight, modular, and category-adapted PEMS are to be expected.

5.6.1.2 Sensor-Based Emission Measurement Systems (SEMS)

SEMS offer an ultralight alternative to conventional PEMS, targeting vehicle categories where weight, size, and energy consumption of full laboratory-grade systems become prohibitive - particularly in the L-category. Unlike PEMS, SEMS rely on compact sensor technology (e.g., electrochemical, NDIR, optoacoustic) and simplified gas conditioning, trading off some accuracy for feasibility and deplorability. SEMS do not typically include an Exhaust Flow Meter (EFM). Instead, exhaust mass flow is either modelled or provided via external data sources - a concept addressed in a subsequent chapter.

Overview of SEMS Prototypes in the Project

Multiple SEMS devices were evaluated within the project. All devices shared a common feature: compact sensor technology and minimal system weight. However, as most are still at the prototype stage, current dimensions and mass reflect early development status. Significant miniaturization is expected in future series production.

HORIBA SEMS

The HORIBA SEMS, developed as part of the LENS project, employs a zirconia-based NOx sensor derived from broadband lambda sensor technology. While this technology shows excellent robustness and calibration stability, it requires a minimum oxygen concentration in the sample gas to function correctly. Since gasoline-powered L-category vehicles typically operate at stoichiometric or rich conditions, the exhaust is often nearly oxygen-free.

To enable sensor operation, a controlled dilution with ambient air is introduced upstream of the sensor. This design includes:

- Ambient air injection (~ppm range)
- NH_3 filtering to avoid cross-sensitivities
- Pressure buffering to mitigate pulsations

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While the overall measurement concept is sound, the requirement for oxygen injection introduces sensitivity to flow fluctuations. Still, the SEMS demonstrated fast response times and reliable NOx data across most test cycles. The use of zirconia technology allows detection of both NO and NO_2.

HORIBA miniPEMS

The HORIBA miniPEMS bridges the gap between full-scale PEMS and lightweight SEMS. It combines:

- A compact NDIR analyser (MEXA 584L, originally designed for stationary use)
- Electrochemical cells (e.g. for NO)
- Pitot-type EFM (for validation purposes)
- GPS, weather module, and onboard data logging

Validation results from the draft paper [24] show good correlation with laboratory-grade analysers, particularly for CO and CO_2. Limitations were noted for:

- Hydrocarbons (NDIR only captures alkanes; FID would be required for full spectrum)
- NO (response lag and drift of electrochemical cell)

Despite these limitations, the miniPEMS showed solid performance for mid-power vehicles and was successfully mounted on several motorcycle types. Notably, power consumption and weight (~12–14 kg total) were kept low through the use of $LiFePO_4$ batteries and passive condensation control (no heated lines).

EMISIA ReTEMS System

The ReTEMS unit developed by EMISIA within the LENS project was designed to enable real-world emissions testing on small motorcycles. It integrates:

- NDIR sensor for CO_2
- Electrochemical sensors for CO and NO
- Novel optoacoustic sensor for black carbon (BC)
- Heated sampling line and modular flow system
- Dilution control via MFCs and calibration with CO_2 span gas

Validation on a chassis dynamometer with WMTC and RDC cycles showed acceptable correlation with reference instruments for:

- Black carbon (vs. MSS)
- NO (vs. PEMS/CLD)
- CO and CO_2 (vs. PEMS/NDIR)

The ReTEMS system represents the first known SEMS capable of simultaneously measuring gaseous pollutants and black carbon, and is expected to significantly contribute to L-category emissions research. Despite being a prototype, future versions aim to halve the system weight (from 4 kg to ~2 kg) and footprint, enabling broader vehicle compatibility.

Czech University of Life Sciences in Prague Mini-PEMS system

The CZU Mini-PEMS [25] samples raw undiluted exhaust, which is cooled, reheated and filtered, and passed through a NDIR optical bench for HC, CO and CO2 analysis, and then through fast response electrochemical cells for NO and O2. The unit includes a 5 Hz GPS receiver, several methods for determining engine rpm (ignition sensor, optical sensor, vibration sensor, alternator ripple sensor), intake manifold pressure and temperature sensors. The 40x20x20 cm unit weighs 9 kg and includes a battery for 3-4 hours of operation.

Several options for flow measurement are possible – speed-density calculation from engine rpm and intake manifold pressure, direct measurement of exhaust flow by high-speed Pitot tube, fuel injector signal logger

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recording fuel injector pulse width and engine rpm, and OBD interface. All flow measurement options rely on calibration/validation of individual vehicles, i.e., on chassis dynamometer over selected operating points.

IFP Energies nouvelles REAL-e system

The REAL-e system, developed by IFPEn, was initially designed as a SEMS for light-duty vehicles, but with few modifications, it was adapted for the LENS project to be used on L-category vehicles. It combines physical gas analysers with modelling techniques to improve data accuracy, eliminating the need for exhaust mass flow measurement – meaning the system does not need to be mounted in a sealed manner on the exhaust.

REAL-e is designed to balance performance and cost, being built with PTI equipment and IFPEn's own components. It includes:

- A heated NDIR (from PTI), measuring CO2, HC n-hexane and CO
- An ECC (from PTI) for O2 and NOx
- An ExtDC (from PTI) for PN
- A UV-DOAS (developed in-house) for NO, NO2 and NH3
- An OBD Dongle for GPS info and OBD data

To evaluate the mass emissions of pollutant, the measure is enriched with the use of dynamics models that estimate the CO2 emissions (or fuel consumption). The enrichment process estimates mass emissions over a trip by combining modelled CO_2 emissions with the ratio of measured gas concentration to measured CO_2 concentration, following equations derived from EU 2017/1151 Appendix 3, as detailed in formulas (Equation 1, Equation 2, and Equation 3).

$$\dot{m}_{\mathrm{CO_2}} = c_{\mathrm{CO_2}} \cdot u_{\mathrm{CO_2}} \cdot q_{\mathrm{mew}} \qquad \text{Equation 1}$$

$$\dot{m}_{\mathrm{gas}} = c_{\mathrm{gas}} \cdot u_{\mathrm{gas}} \cdot q_{\mathrm{mew}} \qquad \text{Equation 2}$$

$$\dot{m}_{\mathrm{gas}} = \frac{c_{\mathrm{gas}}}{c_{\mathrm{CO_2}}} \cdot \frac{u_{\mathrm{gas}}}{u_{\mathrm{CO_2}}} \cdot \dot{m}_{\mathrm{CO_2}} \qquad \text{Equation 3}$$

Where:

- $\dot{m}$ the mass flow of a gas (including CO2) in the exhaust
- c is its concentration
- u is a constant for a given gas and used fuel
- q_{mew} is the exhaust mass flow.

Discussion and Outlook

While SEMS and miniPEMS devices currently vary in terms of sensor types, integration depth, and target pollutants, they share common potential:

- Substantial weight and size reduction compared to traditional / type-approval PEMS
- Feasibility for small motorcycles and scooters (L1e, L3e-A1)
- Compatibility with alternative mass flow estimation methods

However, all current systems remain pre-certification prototypes, and cannot yet replace PEMS in regulatory applications. Nonetheless, their measured deviations fall within acceptable ranges for use in:

- Fleet screening
- Research and development
- Tampering detection
- Emissions trend monitoring

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In future iterations, systems like HORIBA SEMS and ReTEMS could evolve into robust, widely deployable SEMS platforms for L-category vehicles, especially once external exhaust mass flow input becomes standardized.

5.6.1.3 Mobile Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-Transform Infrared Spectroscopy (FTIR) represents a powerful and well-established measurement technology for real-time exhaust gas analysis. In mobile applications, FTIR systems allow the simultaneous detection of a wide range of gaseous pollutants, including nearly all regulated components (CO, CO_2, NO, NO_2, and various organic compounds, with estimated total HC) as well as numerous unregulated substances such as NH_3, HCHO, N_2O, or individual hydrocarbon species. Their high spectral resolution and broad wavelength coverage make FTIR particularly attractive for detailed emission characterization.

Working Principle and System Architecture

Mobile FTIR systems typically consist of the following components:

- Heated gas cell with long optical path (to increase sensitivity)
- Broadband IR source and interferometer
- Detector unit (usually cooled MCT or DTGS sensor)
- Gas conditioning unit (heated sampling line, filters, condensate traps)
- Vacuum pump system for flow control
- Data acquisition and spectral deconvolution software

The measurement principle is based on the absorption of IR radiation by molecular bonds at characteristic wavelengths. The interferogram generated by a Michelson type interferometer undergoes Fourier transform to obtain a single beam spectrum, which is divided by the background spectrum to obtain the absorption spectrum, which is a convolution of absorption spectra of all compounds present in the sample. The absorption spectrum is deconvoluted using reference spectra to quantify the concentrations of gases present in the analysis matrix. The spectra can be later (ex-post) reanalysed for additional compounds. Unlike NDIR systems, FTIR is inherently multi-component capable, enabling analysis of complex exhaust mixtures without needing multiple sensor channels.

Application in Motorcycle Emission Testing

In the context of this project, mobile FTIR was evaluated for its potential use on L-category vehicles. Particular emphasis was placed on:

- Capability to measure non-regulated pollutants (e.g., NH_3, CH_2O)
- High-resolution hydrocarbon speciation (e.g., methane vs. ethylene)
- Possible use as a reference system for verifying sensor-based SEMS
- However, several challenges arise when applying FTIR to motorcycles:
- High system weight: typical portable FTIR systems (e.g., AVL AMA FTIR, MKS, or Horiba ONE-FT) range from 35 to 70 kg including batteries and peripherals.
- High vibration sensitivity: mechanical shock and road-induced vibration can degrade interferometer performance or require frequent recalibration.
- Complex installation: secure mounting on two-wheelers is difficult due to space constraints and limited load capacity.
- Power demand and thermal management: most FTIRs require 230 V AC supply or large battery units with active cooling, limiting autonomous operation.

Due to these factors, on-vehicle installation was envisioned to be generally feasible only for larger motorcycles (e.g., L3e-A3, L5e) or trailer-based setups. Alternatively, FTIR systems are highly suitable for use in chassis

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dynamometer correlation studies, where they can serve as a laboratory-grade reference for validating SEMS or PEMS systems, particularly for extended pollutant species.

Czech University of Life Sciences (CZU) in Prague mobile FTIR system

For reference measurements and to collect non-regulated emission a mobile FTIR from CZU was used. Although this instrument is not in a mass production but prototype status, it can serve as base for future mobile FTIR solutions. A detailed description can be found in ANNEX II "Czech University of Life Sciences in Prague mobile FTIR system".

Evaluation Summary

While mobile FTIR technology offers unmatched analytical capabilities, its current form factors and integration requirements restrict its use in RDE tests to bigger vehicles. Additionally, thorough optimization of FTIR systems for size, mass, power consumption and resistance to weather and vibrations is necessary for its use on L-category vehicle. Table 13 summarizes key characteristics of standard mobile FTIR solutions and the prototype FTIR used in LENS:

Table 13: Key characteristics of standard FTIR instruments

Characteristic	Standard mobile FTIR	Prototype FTIR used in LENS
Pollutant coverage	Very broad (incl. unregulated compounds)	All Euro 7 pollutants except total HC
Accuracy / Resolution	High	High
Response time	Medium (typically 1–2 Hz sampling)	5 Hz, t90 < 2 s
Weight	High (35–70 kg)	35 kg (45kg)[21]
Power requirement	High (mains power or large battery)	200 Watts
Mounting feasibility	Limited (L3e-A3+, trailer setups)	Limited due to weight and size (L3e-A1 and bigger)
Sensitivity to vibration	High (requires damping or lab use)	Moderate
Suitability for type approval	Potentially (with adaptation)	Potentially (with adaptation)
Recommended use in project	speciation studies	speciation studies

Conclusion

Mobile FTIR systems are best regarded as advanced reference instruments rather than mainstream field tools for L-category vehicles. Their strengths lie in comprehensive gas analysis and post-processing accuracy. For actual on-road integration in smaller vehicle categories, further miniaturization and ruggedization would be essential. An approach was shown within the project, whereas further work must be done for feasibility in type approval test procedures.

5.6.1.4 Exhaust Mass Flow Assessment

Accurate measurement of the exhaust mass flow is essential for the calculation of mass-based emission rates during RDE testing. However, particularly in the context of motorcycles and other L-category vehicles, the physical constraints of the exhaust system (e.g., short pipes, small flow volumes, strong pulsations) often limit the applicability of standard Pitot-based exhaust flow meters (EFMs). As a result, alternative, model-based approaches have been explored within the project.

[21] with external frame backpack, batteries, inverter, sampling line

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Model-Based Mass Flow Estimation Using OBD Parameters (TU Graz)

An innovative and non-invasive method for estimating exhaust mass flow has been developed and patented by TU Graz. The method is based on the following workflow:

- Test Bench Data Acquisition: Exhaust mass flow is measured using a certified reference system (e.g., CVS) while simultaneously logging OBD data (e.g., standard PIDs defined by SAE J1979).
- Parameter Screening: Engine parameters such as engine speed, load, intake manifold pressure, and air temperature are analysed for their suitability in correlating with mass flow.
- Model Training: A neuro-fuzzy algorithm is used to partition the data space and generate best-fit polynomials for each sub-region, resulting in a regression model.
- Verification: Performing another test bench test, utilizing a different driving cycle to the cycle used for the model training.
- On-Road Application: The trained model is deployed on-road using standard OBD data loggers to estimate real-time mass flow without any physical intervention in the exhaust tract.

Advantages:

+ Fully non-invasive (no hardware modifications or intrusive sensors required)
+ Minimal instrumentation effort in on-road use
+ Can be implemented on a wide range of modern vehicles (EURO 4+)

Limitations:

- Requires access to a chassis dynamometer for model training
- Limited to OBD-compliant vehicles with sufficient signal availability
- Operating range depends on the coverage of operating points during training
- Accuracy depends on the reference utilized for the lab tests

Injector Pulse Width Mapping (CZU Prague)

An alternative model-based method has been developed by CZU in Prague. In this approach, the exhaust mass flow is derived from the measured exhaust gas composition and from the fuel flow inferred from injector pulse width measurements:

- Test Bench Mapping: The injector pulse width is recorded using an oscilloscope during steady-state and transient test bench runs.
- Model Generation: A lookup model is created to map pulse width to fuel volumetric flow for a given engine and a given fuel in the tank. An assumption is made that the fuel temperature and pressure during on-road test are comparable to those during the mapping.
- On-Road Logging: During RDE trips, the injector signal is again captured via oscilloscope to estimate the instantaneous fuel mass flow using the pre-established map.

Advantages:

+ Accurate within the calibrated range
+ Independent from OBD protocols or ECU access
+ Particularly suitable for engines where injector wiring is accessible
+ Since the air-fuel ratio used for exhaust flow calculation and the exhaust composition are determined from the same gas analyser, errors caused by exhaust dilution (backflow of outside air into the exhaust, common on small single-cylinder engines; to large extent unavoidable as installations of sampling lines avoiding backflow may alter engine operation) cancel out, therefore, the mass emissions calculations are not affected by exhaust dilution.

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Limitations:

- Requires oscilloscope-based signal acquisition (technical setup complexity)
- Also dependent on test bench mapping
- May not generalize well outside trained load/speed regions
- Changes in fuel density (temperature-dependent) and pressure affect the accuracy of the measurement.

Note on Adapted Pitot-Based EFM Application

Despite the general limitations of Pitot-based exhaust flow measurement in the context of motorcycles—such as low flow rates, strong pressure pulsations, and short exhaust systems—one specifically adapted system, used and further developed during the project, showed notably robust performance.

Through mechanical adaptations and optimized signal processing, the applied EFM unit was able to provide usable and consistent mass flow data even in challenging configurations, including single-cylinder and small-displacement motorcycles. While limitations remain in dynamic resolution and accuracy at the lower end of the mass flow range, the system proved suitable for the majority of test vehicles within the project scope.

This confirms that, with appropriate modifications, Pitot-based systems can remain a viable option for certain motorcycle categories (e.g., L3e-A2/A3), particularly where physical integration is feasible and mass limitations are acceptable.

Comparison to Conventional Pitot-Based EFMs

The following table summarizes the main characteristics of the three discussed methods:

Table 14: Main characteristics of exhaust flow measurement methods

Criterion	Pitot-Based EFM	OBD-Based Model (TU Graz)	Injector Mapping (CZU Prague)
Accuracy (ideal conditions)	High	Medium to high	High
Sensitivity to pulsations	Very high	Low	Low
Requires chassis dynamometer	No	Yes	Yes
On-road applicability	Limited (due to size and weight)	High	Medium
Additional hardware required	EFM, Hosing, Supply	OBD-Logger	Oscilloscope, Signal acquisition, Logger
Signal access	Direct (via tailpipe connection)	Standardized OBD-II (EURO 4+)	Direct injector wiring
Usability on L1e / L3e-A1 vehicles	Rarely feasible	Feasible (if OBD available)	Feasible (if injector signal accessible)
Certification status	Certified under EU RDE-LDV (Reg. 2017/1151)	Research application (patented)	Research application (not certified)
Measurement range limitations	Inaccurate at low flow and high pulsation	Limited to trained test bench range	Limited to test bench mapping
System weight and packaging	High	Very low	Medium
Effects on engine behavior	possibly	No	None observed

5.6.1.5 Summary and System Suitability Matrix

The evaluation of various emissions measurement technologies for L-category vehicles has shown that no single system currently meets all requirements across every vehicle type and application. While certified PEMS units offer the highest measurement accuracy, they are often too heavy or bulky for small motorcycles. Miniaturized

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alternatives like miniPEMS and SEMS offer significantly better integration potential but come with trade-offs in measurement accuracy, pollutant coverage, and certification status. Mobile FTIR systems provide exceptional analytical capabilities, especially for non-regulated compounds, but are currently impractical for direct on-vehicle use due to their size, weight, and sensitivity to vibrations. The table below (Table 15) summarizes the core attributes, strengths, and application limits of each system type.

Table 15: Core attributes, strengths, and application limits of portable emission measurement systems

Criteria	**Certified PEMS**	**miniPEMS**	**SEMS**	Mobile FTIR
System weight	~50 kg	~12–14 kg	~4–8 kg (prototype)	~45 kg (prototype)
Power supply	exchangeable battery	Internal (~2.5 h)	Internal (~2.5 h)	exchangeable battery
Mass flow measurement	Yes (Pitot-EFM)	Optional	Optional	No
Pollutants measured	CO, CO_2, NO, NOx, PN	CO, CO_2, (HC), NO	NOx, CO, CO_2, BCP	Gaseous (incl. NH_3, HCHO, N_2O…)
Measurement accuracy	High (certified)	Acceptable–High (validated)	Acceptable-Medium (prototype status)	High (lab-grade)
Certification status	EU RDE LDV-compliant	Non-certified (experimental)	Non-certified (prototype)	Non-certified (reference only)
Installation effort	Moderate-High	Moderate	Low	Very high
Vibration sensitivity	Low	Low	Low	Medium
Estimated cost	High	Medium	Low–medium	High

The following matrix (Table 16) summarizes the practical applicability of each system type across various L-category vehicle classes and test scenarios. It highlights where each technology can be realistically deployed, considering constraints such as weight, installation complexity, and measurement capability. While certified PEMS remain the benchmark for regulatory testing, lightweight alternatives like miniPEMS and SEMS significantly expand feasibility for small vehicles and exploratory testing. FTIR systems, although highly capable analytically, are currently best used in controlled laboratory environments or as mobile reference tools.

Table 16: Applicability of different portable measurement equipment for the different L-categories

Vehicle / Application	**PEMS**	**miniPEMS**	**SEMS**	**FTIR**
L1e (50cc mopeds)	⊖	⊙	⊕	⊖
L3e-A1 (125cc motorcycles)	⊙	⊕	⊕	⊙
L3e-A2 / A3 (250–400cc)	⊕	⊕	⊕	⊙
L5e / L6e / L7e (trikes/quads)	⊕	⊕	⊕	⊙
Suitable for type approval / legal conformity	⊕	⊖	⊖	⊖
Research & development	⊕	⊕	⊕	⊕
On-road RDE testing	⊙	⊕	⊕	⊙
Unregulated compounds	⊙	⊖	⊖	⊕
Tampering detection / fleet monitoring	⊙	⊕	⊕	⊖
Laboratory validation / reference	⊕	⊕	⊕	⊕

⊖ - minor applicability / ⊙ - moderate applicability/ ⊕ - well applicable

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5.6.2 Measurement equipment for additional emission components

As discussed in chapter 2.2 several non-regulated[22] emission components reach high values, exceed in some cases the limits of other vehicle categories and are recommended for inclusion in type approval measurements (chapter 5.3). In the following, necessary measurement instruments are discussed.

5.6.2.1 Solid Particle Number (SPN)

During the laboratory testing campaign, several L-category vehicles with spark-ignition (SI) engines exhibited elevated solid particle number (SPN) emissions, particularly during transient driving conditions. These emissions were notably high during acceleration phases involving fuel enrichment, whereas emissions under steady-state or idle operation remained low due to stoichiometric combustion. This results in a strong base-to-peak ratio, i.e., short high-concentration peaks in contrast to low baseline levels during normal operation.

Due to the very short exhaust systems in most motorcycles and the lack of particle deposition surfaces, the emitted particles tend to remain in their primary size distribution, often centred around 20–25 nm. In many models, the catalytic converter is integrated into the muffler, which can result in elevated exhaust gas temperatures even at the rear of the vehicle. Combined with short pipe lengths, this makes standard automotive sampling interfaces (e.g., silicone couplings) unsuitable, necessitating metallic sampling connections.

SPN measurements conducted within this project, based on SPN10 instrumentation, showed that particle counts below the light-duty vehicle LDV regulatory cutoff of 23 nm can dominate total emissions, especially in SI-powered motorcycles and mopeds. This highlights a major blind spot in current regulations and supports the case for extending particle number legislation to L-category vehicles.

These findings strongly support the introduction of SPN measurements in future type approval procedures for L-category vehicles. Furthermore, they demonstrate that the measurement methodology developed for LDV can largely be transferred, provided that certain adaptations are made for the unique exhaust and engine characteristics of motorcycles.

Measurement Methodology and Normative Base

The SPN measurement methodology is well-established in the LDV sector, with clear requirements defined in a series of international and European regulations. The current standard is based on the detection of solid, non-volatile particles larger than 23 nm using a Condensation Particle Counter (CPC), preceded by a Volatile Particle Remover (VPR). The VPR ensures that only non-volatile solid particles are counted, typically using a catalytic stripper in the latest standards.

The following regulations form the core framework for SPN measurement in passenger cars:

- UN/ECE Regulation No. 83 (Annex 4A), which first introduced SPN limits for diesel vehicles (Euro 5b) and extended them to gasoline DI engines under Euro 6
- EU Regulation No 2017/1151, implementing the WLTP test procedure, with detailed requirements for both SPN lab and RDE testing
- GTR No. 15, the Global Technical Regulation that harmonizes LDV type approval procedures and includes SPN methods
- The Particle Measurement Programme (PMP) by UNECE, which provides the technical and procedural foundation for SPN instrumentation, calibration, and validation

In addition, supporting standards such as ISO 27891 (CPC calibration) and CEN/TS 16911 (PN system specifications) ensure harmonized performance across different laboratories and manufacturers.

[22] Non-regulated in EU Regulation No 167/2013

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Relevance for L-Category Vehicles

Transferring this measurement methodology to L-category vehicles is technically feasible and scientifically justified. The same CPC-based setup used in LDV testing can be employed, with adjustments to:

- Dilution ratio adjustment: The strong concentration fluctuations in SI motorcycles (high peaks during enrichment, low background during stoichiometric operation) requires a dilution strategy depending on the counters measuring range.
- Backpressure control: The influence of sampling resistance must be minimized to avoid altering engine performance, especially in low-displacement engines.
- Exhaust interface adaptation: High exhaust gas temperatures at the muffler, and close proximity of the catalyst, necessitate metallic, heat-resistant connections. Silicone tubing, commonly used in passenger car setups, is often unsuitable.

From a regulatory perspective, the SPN methodology could initially be introduced as a development tool, e.g. in emissions research, environmental impact studies, or to support the design of future emission control systems for motorcycles. In a subsequent step, it could be formalized within a GTR annex or included in future revisions of Euro 5/6 for L-category vehicles.

It is important to note that current legislation (Euro 6 and GTR 15) focuses exclusively on SPN23. However, as the measurements in this project have shown, SPN10 is a far more relevant metric for motorcycles, given their emission behaviour and particle morphology. The adoption of SPN10 instrumentation, which is already under evaluation in the context of Euro 7 and heavy-duty regulations, would significantly improve the representativeness of particle number measurements in small engines and short exhaust systems.

5.6.2.2 Particle Mass Emission (PM)

Particulate mass (PM) emissions are already regulated for certain subcategories of L-category vehicles under current legislation, primarily targeting GDI and CI engines. These regulations follow the structure used in passenger car legislation, employing gravimetric filter-based methods using CVS systems in laboratory environments. However, based on the results obtained in this project and supported by multiple prior studies, there is no technical justification for extending PM limits to the remaining L-category engine concepts, such as small motorcycles and mopeds. This assessment is directly linked to the fundamental particle characteristics emitted by these vehicles. As previously discussed in the context of SPN emissions, the primary particle diameters in SI L-category vehicles are often well below 30 nm, with measured median values in the range of 20–25 nm. Such particles are ultrafine and typically consist of nucleation-mode soot or semi-volatile organic material. While these particles contribute significantly to particle number, their individual mass is extremely small. From a physical standpoint, the mass of a spherical particle scales with the cube of the diameter; for carbonaceous particles with fractal shape, the particle mass is proportional to the particle diameter to the power of fractal dimension, and is closer to square of the particle diameter. Consequently, the overall particulate mass emissions from such vehicles remain very low, often below the detection limit of gravimetric methods. Instead, SPN - particularly in the SPN10 range - offers a far more sensitive and relevant indicator.

5.6.2.3 Ammonia NH_3

Ammonia (NH_3) is a toxic byproduct formed during the operation of three-way catalytic converters (TWC) and selective catalytic reduction (SCR) systems. Although not classified as one of the primary regulated pollutants (such as CO, HC, or NO_x), NH_3 has gained increasing regulatory attention—particularly in the context of Euro 6d and the upcoming Euro 7 legislation.

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Approved and Recommended Measurement Technologies

While the regulatory requirement for NH_3 measurement is still emerging (see chapter 4.2.2), several technologies are already accepted or widely used in type-approval laboratories (Table 17).

Table 17: Technologies for NH_3 measurement

Technology	Principle	Usage / Status
FTIR (Fourier-Transform IR)	Spectral absorption of IR radiation	Widely accepted and used
QCL (Quantum Cascade Laser)	High-resolution infrared absorption	High-end research and precision labs; latest equipment
PAS (Photoacoustic Spectroscopy)	IR absorption converted to acoustic signal	Compact, sensitive, emerging technology
Electrochemical sensors	Redox-based detection via membrane	Low-cost, but limited selectivity
UV-DOAS (UV-Differential Optical Absorption Spectroscopy)	Spectral absorption of UV radiation	Compact and sensitive

Among these, FTIR is currently the most used method in LDV test benches and is explicitly referenced in GTR 15 Annex 7 as an appropriate technique. Commercial systems deliver real-time NH_3 concentration measurements with detection limits in the range of 0.5–1 ppm.

QCL-based systems offer even higher resolution and specificity (sub-ppm range), but they are more costly and typically used in calibration labs or research setups. PAS sensors are promising for compact applications but are not yet widespread in type-approval use.

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11 Table 1-10 of ANNEX II of Commission delegated Regulation (EU) No 134/2014 of 16 December 2013

12 Appendix 9 of ANNEX II of Commission delegated Regulation (EU) No 134/2014 of 16 December 2013

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7 ANNEX I Determination of real-world running resistance

7.1 Background and objectives

Measuring L-category vehicles in a laboratory setting requires that the chassis dynamometer is set in such a way that the vehicle experiences the same running resistance as it would while driving on the road. For example, there is no wind speed in the laboratory, therefore the air drag is simulated by the chassis dynamometer. The procedure for this is described in EU Regulation No 134/2014, and consists of two steps:

1. A coast-down test procedure to determine the on-road running resistances, referred to as the 'road-load', as specified in Appendix 7 or Appendix 5 of EU Regulation No 134/2014.
2. A procedure to set the chassis dynamometer to reproduce the road load, as specified in Appendix 3 of EU Regulation No 134/2014

As an alternative to the coast-down test, the regulation also provides standard values in the form of a running resistance table in Appendix 5 of EU Regulation No 134/2014. This specifies a set of standardised f_0 and f_2 coefficients as a function of the vehicle reference mass in bins of 10 kg.

As an alternative, Appendix 5 of EU Regulation No 134/2014 offers the possibility to apply standard values for setting the chassis dynamometer, which are based solely on the mass of the vehicle, so without the need for measuring the actual running resistance.

The procedure for the determination of the actual road-load requires that a vehicle is tested on a test track, where it is coasted down in neutral gear (or with the clutch disengaged) from a high speed (at least 125 km/h) down to a low speed (15 km/h or lower) over sufficiently long straights and in opposite driving directions. During the coast-down test, the weather conditions need to be stable, with preferably as low windspeed as possible. There are multiple boundary conditions prescribed for this test, for example, the maximum average windspeed allowed in the driving direction is 3 m/s, see the next paragraph for all ambient conditions. During the processing of the test results, the coast-down times are corrected towards standard ambient conditions. Then, the road-load is determined as a polynomial curve with two coefficients (a constant coefficient f_0 and a second order coefficient f_2)[23].

One of the subtasks specified in WT 3.2 is to "determine the real-world running resistance to provide better comparison between on-road and lab tests". The LENS partners TNO and IDIADA have executed this task by performing road-load measurements on a total of four motorcycles. In addition, data was gathered via the LENS partners. These results were then compared to the table values of Appendix 5. The results are described in the following sections.

7.2 Data collection

The first step for the analysis of real-world running resistances is to search for data among the LENS partners and in literature. There was no information found in literature, because of the following reasons:

[23] Note that this is different from the WLTP coast-down test procedure for light-duty vehicles in EU Regulation No 2017/1151, which also includes a first order coefficient f_1.

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- It is suspected that nearly all manufacturers of L-category vehicles use the table values of Appendix 5 to EU Regulation No 134/2014, so there is not much data available on the real-world road-load. There is no actual proof of this assumption, but if the results of this investigation are generally valid for all motorcycles, it is understandable why this is the case since using the table values is much less complicated;
- Road-load data is normally seen as sensitive, and therefore treated as confidential information. It is uncommon to publicise this to a wider audience.

However, KTM was kind enough to share data on one motorcycle, for which they established the real-world road-load with LENS.

7.3 Coast-down testing

In the absence of any further useful data, coast-down measurements on four different motorcycles were organized, refer to Table 18 for the specifications.

Table 18: Test vehicle characteristics

				
Make	BMW	Yamaha	Yamaha	Ducati
Model	R1250 GS Adventure	MT-09 (MTN890)	R7 (YFZ690)	Panigale V2
Rated power	100 kW	87.5 kW	54 kW	114 kW
Secondary Driveline	Shaft drive	Chain drive	Chain drive	Chain drive
Category	L3e-A3	L3e-A3	L3e-A3	L3e-A3
First registration	20-01-2024	07-05-2024	28-03-2025	
Odometer reading	16900 km	9080 km	1558 km	975 km
Empty mass (OEM specification)	261 kg	193 kg	181 kg	176 kg
Test mass including driver	344 kg (average)	262 kg (average)	257 kg	307 Kg
Test by	TNO	TNO	TNO	IDIADA

The test objects were relatively new but can be considered as fully run-in as they all had driven sufficiently long distances. The TNO test driver having a mass of approximately 70 kg and a height of 1.73 meter, while the IDIADA test driver had a mass of approximately 75 kg and a height of 1.80 meter.

The BMW had an adjustable ride-height setting, which was set to the lowest position, expecting this to lead to the lowest air drag. Both Yamahas did not have such a setting. Coasting-down was for all vehicles performed with the vehicle transmission in the neutral position and the clutch disengaged.

The test equipment used was the same for TNO and IDIADA. Care was taken to ensure all equipment used was properly calibrated. Time and the speed of the vehicle during the coast-down tests were logged by a Racelogic VBOX GPS data logger combined with an Inertial Measurement Unit (IMU, an accelerometer) to improve the quality of parameters measured. The specifications of this device are listed in Table 19. Signals from the GPS and the IMU were processed and filtered by applying a Kalmann filter. Heading, altitude, and location were also

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recorded but not used. The GPS equipment is well-known and commonly used for performing coast-down tests. The software included is specifically designed for coast-down tests and updated to the latest WLTP requirements for light-duty vehicles.

Table 19: GPS equipment specifications

GPS equipment	
Model	Racelogic VBOX 3i v2, with IMU
Time accuracy	0.01 s
Time resolution	0.01 s
Velocity accuracy	0.1 km/h
Velocity resolution	0.01 km/h
Distance accuracy	0.05%
Distance resolution	1 cm
Update rate	100 Hz
Latency	6.75 ms

Measurement instruments were installed behind the driver to avoid that they cause higher air drag. Furthermore, there were no accessories installed such as travel-suitcases. Before and after the coast-down measurements the vehicles were weighed. Tire pressures were set to the manufacturer recommended values in cold condition. The vehicles were technically inspected and the wheels were checked for any parasitic losses, e.g. from the brake pad touching the brake disc. These inspections and the tire pressure checks were conducted before, during and after the tests.

The coast-down tests were largely executed in accordance with the test procedure as specified in Annex 7 to EU Regulation No 134/2014. One exception was made: the coast-down times for all target vehicle speeds v_j were measured from v_j + 5km/h to v_j - 5km/h (this is more accurate, and consistent to the WLTP coast-down procedure for passenger cars in EU Regulation No 2017/1151). The coast-down times at each of the relevant target vehicle speed intervals (i.e., 120, 100, 80, 60, 40 and 20 km/h) were measured in both driving directions, and a selection of run-pairs was made to arrive at the lowest value for the statistical accuracy P (refer to Equation Ap7-4 in EU Regulation No 134/2014).

According to the Regulation, the ambient conditions have to fulfil the following limits:

- maximum wind speed: 3 m/s
- maximum wind speed for gusts: 5 m/s
- average wind speed, parallel: 3 m/s
- average wind speed, perpendicular: 2 m/s
- maximum relative humidity: 95 percent
- air temperature: 278.2 K to 308.2 K

Standard ambient conditions shall be as follows:

- pressure P_0 = 100 kPa
- temperature T_0 = 293.2 K.

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Table 20: Test vehicle conditions for the coast-down testing

				
Make	BMW	Yamaha	Yamaha	Ducati
Model	R1250 GS Adventure	MT-09 (MTN890)	R7 (YFZ690)	Panigale V2
Test site	RDW Test Centre	RDW Test Centre	RDW Test Centre	IDIADA
Track length	Oval track, 720 m. straight line	Oval track, 720 m. straight line	Oval track, 720 m. straight line	Oval track, 2km straight line
Track slope	level	level	level	North/south straight: +0,3 %/-0,3%
Air temperature	29 °C	10 °C	25 °C	14,3°C
Maximum wind speed	3.5 m/s	5 m/s	10 m/s	1,3 m/s
Speed range	125 to 15 km/h	125 to 15 km/h	125 to 15 km/h	125 to 15 km/h
Number of runs	5	5	8	6 runs
Max p	5.9 (excl. 125 km/h)	9.6	10.8 (excl. 125 km/h)	3,38

The vehicles were tested on days with fairly stable weather conditions, see Table 20. The above listed wind criteria were met for the coast-down test of the Yamaha MT-09. For the test of the BMW and the Yamaha R7 the wind conditions were nearly met, with slightly higher cross-winds was slightly higher (up to 5.5 m/s). the statistical accuracy criterion ($P \leq 3\%$) could not be fulfilled at every target vehicle speed.

Particularly for the highest target speed of 120 km/h it was challenging to arrive at stable results at the RDW test track. This takes place shortly after the transition from gear to neutral and the track is not entirely level at the start of the straights. Since the track is designed with a banking in the bends and has relatively short straights it is critical to drive at the bend radius where there is the least inclination in the test track.

7.4 Coast-down results

The running resistances were calculated at every target vehicle speed v_j from the average coast-down times of the selected run-pairs. A second order polynomial function is fitted to the measured running resistances of all target speeds by applying the least-squares method as follows:

$$F = f_0 + f_2 . v^2$$

The coefficients f_0 and f_2 have been corrected towards standard conditions following the correction method described in EU Regulation No 134/2014. To avoid any influence of wind, the average windspeed parallel to the straights was used to correct the running resistance, following the correction formula for passenger cars as described in par. 4.5.1. of Sub-Annex 4 to EU Regulation No 2017/1151 (note that in EU Regulation No 134/2014 there is no wind correction foreseen).

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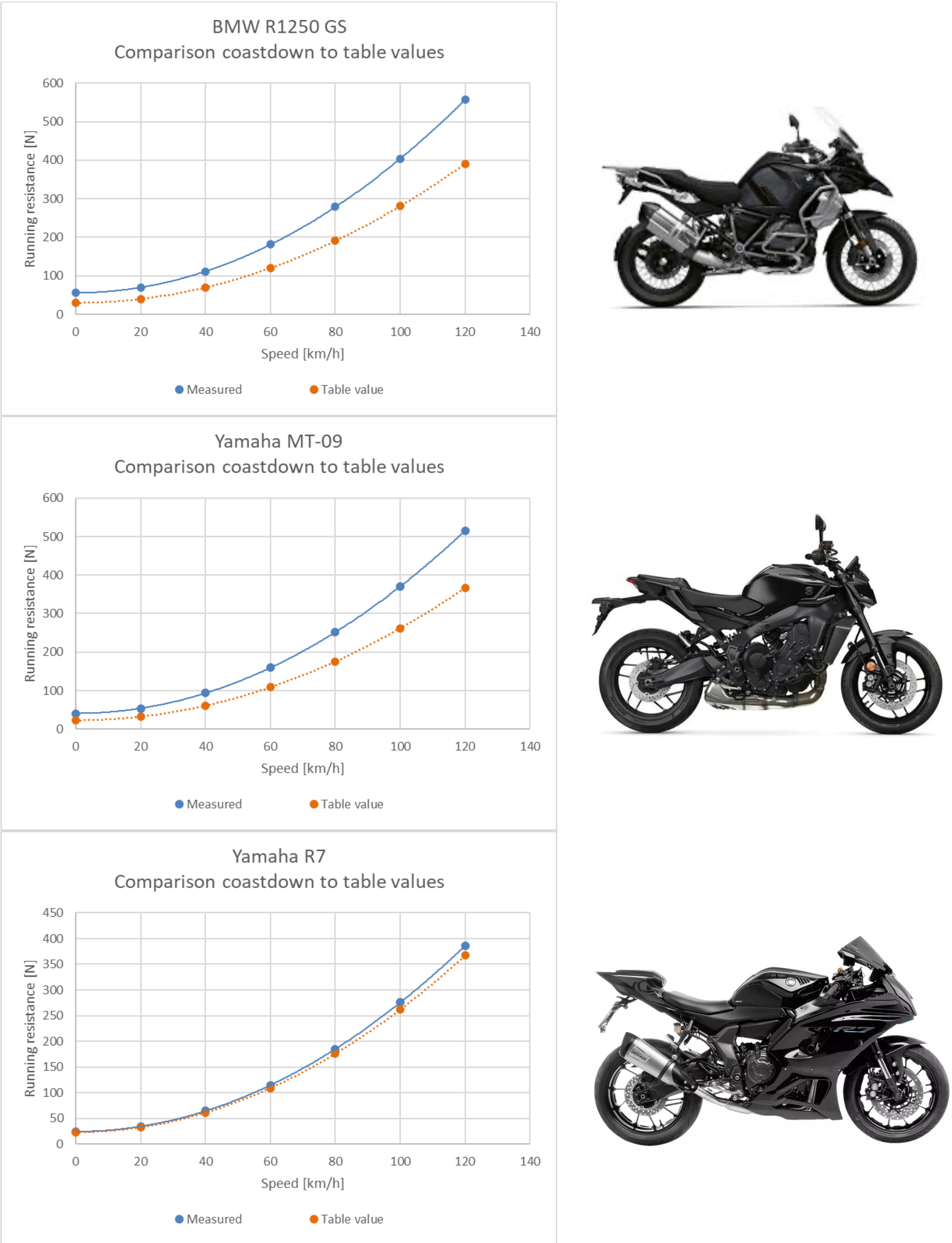

Figure 29: Comparison of coast-down results and table values for BMW R1250 GS, Yamaha MT-09 and Yamaha R7

The graphs in Figure 29 show the running resistances based on the coast-down measurements. The blue curves show the fitted function for the real-world values on the track, while the orange curves show the corresponding table values, i.e., the prescribed f_0 and f_2 coefficients based on the table in Appendix 5 of EU Regulation No

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134/2014. Results have been extrapolated towards 0 km/h, to show the difference in f_0. As will be addressed later in paragraph 7.6 and 7.7, these curves cannot be compared directly. For the Yamaha R7, the measured resistance at reference speed 120 km/h was ignored, as it was an obvious outlier from the fitted curve. For this motorcycle it proved difficult during the coast-down runs to achieve sufficient overspeed to accurately measure the deceleration from 125 to 115 km/h, due to the track layout and the limited power of the vehicle.

Figure 29 shows that the coast-down tests results are significantly higher than the values from the table in Appendix 5 of EU Regulation No 134/2014. In absolute terms, the discrepancy increases with higher speeds, up to a maximum of 166 N for the BMW respectively 148 N for the Yamaha MT-09 and 19 N for the Yamaha R7. The relative discrepancy is the highest at low speeds and decreases towards higher speeds. For the BMW the actual resistance is 42% higher at 120 km/h and 75% higher at 20 km/h. For the Yamaha MT-09 the relative difference ranges from 40 to 78%, which is remarkably consistent to the results of the BMW. For the Yamaha R7 the relative difference is 5% for all of the reference speeds. The fact that the differences are considerably smaller for the Yamaha R7 can be explained from the fact that this motorcycle has an aerodynamically shaped bodywork, where the BMW R1250 and Yamaha MT-09 have a more open body design with higher aero resistance. Such vehicles are normally referred to as 'naked or touring bikes'. Since the table values are only dependent of the vehicle weight, not on its aerodynamic characteristics, the differences between the table values and the coast-down curves are larger for naked bikes.

A coast-down test on a Ducati Panigale V2, a powerful motorbike with an aerodynamically shaped body, was performed by IDIADA. The result of the coast down on the track is presented by the blue curve in Figure 29 while the table value resistance is presented by the orange curve. The absolute difference between these curves amounts from 13 to 21 N, and in relative terms from 3 to 60% (the largest absolute and relative value is at 20 km/h).

Again, it should be noted that, these curves cannot be directly compared to one another as the one is a target value for the chassis dynamometer and the other is a setting value as will be shown in paragraph 7.6 and 7.7.

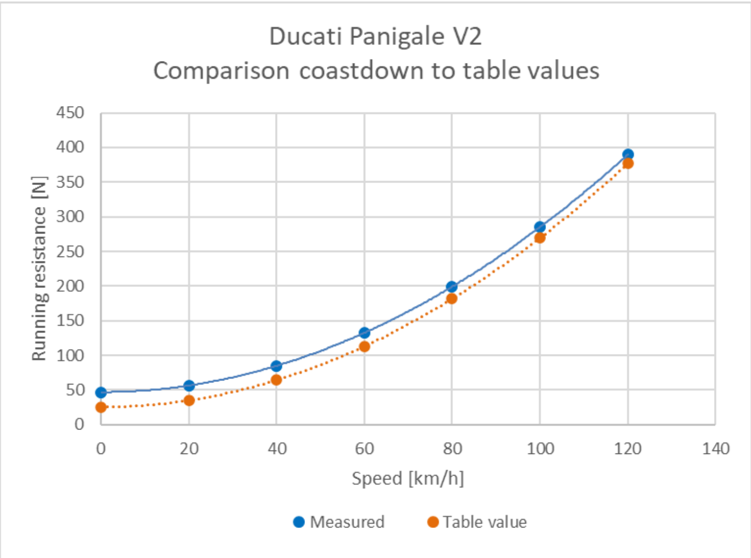

Figure 30: Comparison of coast-down results, table values and coast-down on the chassis dynamometer values for a Ducati Panigale

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7.5 Other coast-down data

7.5.1 Data from KTM

The information received from KTM on the Duke 390 model consists of two separate coast-down datasets for the same motorcycle model (but not the exact same motorcycle) at different test tracks on different dates and for dissimilar (yet overlapping) speed ranges. The results are shown in Figure 31.

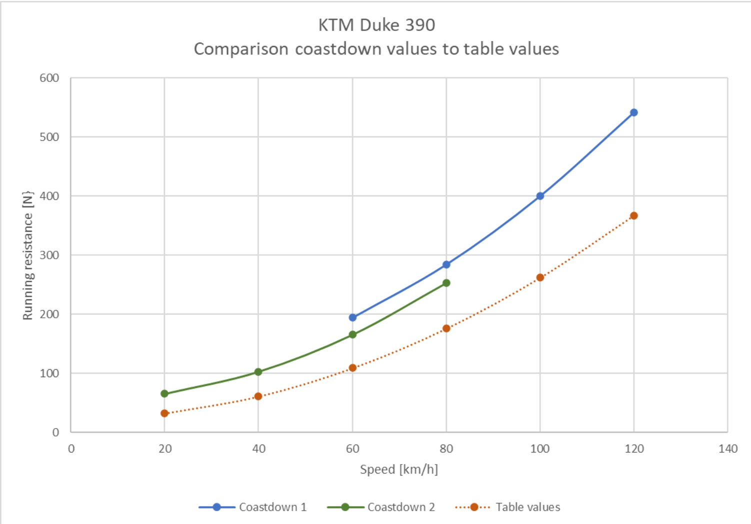

Figure 31: Comparison of coast-down results and table values for KTM Duke 390 (source: KTM)

Even though the two coast-down curves do not overlap in the speed range of 60 to 80 km/h, the figure clearly shows that the resistance from the coast-down tests are higher than the values from the table in Appendix 5 of EU Regulation No 134/2014. Relative differences range from 48% at 120 km/h to 101% at 20 km/h. These results are well in agreement to those measured by TNO. Also here, these curves cannot be directly compared to one another as the one is a target value for the chassis dynamometer and the other is a setting value. This will be shown in paragraph 7.6 and 7.7.

7.5.2 Aero drag rider position comparison

Another interesting investigation by IDIADA on the Ducati Panigale V2 concerned the influence of the position of the driver. According to EU Regulation No 134/2014 "the rider shall be seated on the seat provided, with his feet on the footrests and his arms extended normally". This means that the driver has an upright position. This resulted in the blue coast-down curve in Figure 30. Next, they conducted the same coast-down test procedure with the driver in an aerodynamic position, meaning that he leaned forward to decrease the impact from the wind resistance. The result is shown in Figure 32 by the red line. As expected, the running resistance for low speed is negligible, but for higher speed the difference increases to 71 N at 120 km/h, or 18% lower running resistance for the aerodynamic position. This is not only due to the more favourable position, but also the effect of a lower frontal area of the vehicle/driver combination. This result highlights the sensitivity of the coast-down test for any change in aerodynamics and/or frontal area.

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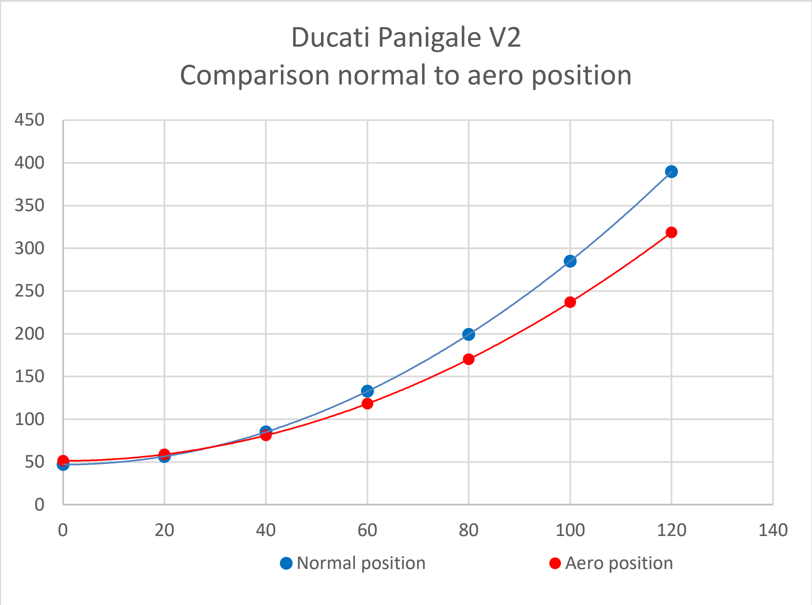

Figure 32: Comparison of coast-down test results with running resistance curves with the driver in a normal position and an aerodynamic position.

7.6 Target setting versus chassis dynamometer setting

Before addressing the consequences of the difference between the measured running resistances and the table values, it needs to be highlighted that actually, these cannot be directly compared to one another. If the on-road running resistance has been measured by a coast-down test procedure, the running resistance curve is used as a *target setting* for the chassis dynamometer. This means that the chassis dynamometer should be adjusted in such a way that the vehicle experiences the same resistance as measured on-road (within a certain tolerance). This can be achieved by performing coast-down runs on the chassis dynamometer, and adjusting its settings in an iterative process until the target resistance curve is replicated. Effectively, the *chassis dynamometer setting* represents the difference between the target resistance curve and the resistance of the test vehicle on the rollers of the chassis dynamometer (mainly rolling resistance). The internal friction of the chassis dynamometer is already compensated for separately by the chassis dynamometer calibration procedure.

The table values from Appendix 5 of EU Regulation No 134/2014 are applied as a chassis dynamometer setting. This means that the rolling resistance of the vehicle will add to the resistance experienced by the vehicle on the chassis dynamometer. Since the rolling resistance of a tyre on the roller depends on the roller diameter and roller surface, effectively the emissions measured on two different chassis dynamometers are not entirely comparable.

It should also be noted that this deviates from the table values for passenger cars, where EU Regulation No 2017/1151 specifies that these should be applied as target road-load values. Applying that same principle for EU Regulation No 134/2014 would be an important improvement to make the results independent of the actual chassis dynamometer used for the measurement. As a consequence, the table values of Appendix 5 would need to be re-established towards a higher resistance to account for the missing chassis dynamometer resistances in the current table values.

From the above it becomes clear that it is not possible to make a direct comparison between the resistance curves based on the table values and the one based on the measured coast-downs on the road. The missing element is the chassis dynamometer resistance, which is specific for every combination of vehicle and chassis

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dynamometer. This resistance should be added to the table values curves in Figure 29 and Figure 30, to become comparable to the measured running resistance by the coast-down method.

7.7 Chassis dynamometer testing

Additionally, a chassis dynamometer setting procedure was performed by IDIADA on the Ducati Panigale V2, where the blue curve from the coast-down test was used as the target running resistance. After three iterations the chassis dynamometer setting came out as the green curve in Figure 33, which is the setting for this specific chassis dynamometer to arrive at the same running resistance as measured during the coast-down measurements on the test track. For this dataset it is possible to compare this directly to the table value curve, which is also a chassis dynamometer setting. The table value curve is slightly higher than the chassis dyno coast-down curve, with differences ranging from 10 N at 20 km/h to 28.5N at 120 km/h (in relative terms, 41 to 8% higher). Therefore, even though the measured coast-down curve on the test track is higher than the table value curve, in reality the exhibited running resistance on the chassis dynamometer will be higher if the table values are applied as chassis dynamometer setting. Important to note with this conclusion is that this is only valid for this particular motorcycle on this particular chassis dynamometer. Considering that the bodywork of the Ducati Panigale V2 is aerodynamically shaped, the situation might look reverse for a naked bike where the table value curve could be lower than the chassis dynamometer coast-down curve. Unfortunately, TNO was not able to perform chassis dynamometer coast-downs to allow for such a comparison for the BMW R1250 and the Yamaha MT-09. However, judging from the differences shown for these vehicles in Figure 29 and the differences between the green and orange curve in Figure 30, there is reason to assume that for these vehicles the table value curve would underestimate the chassis dynamometer setting needed to replicate the blue coast-down curve on the chassis dynamometer.

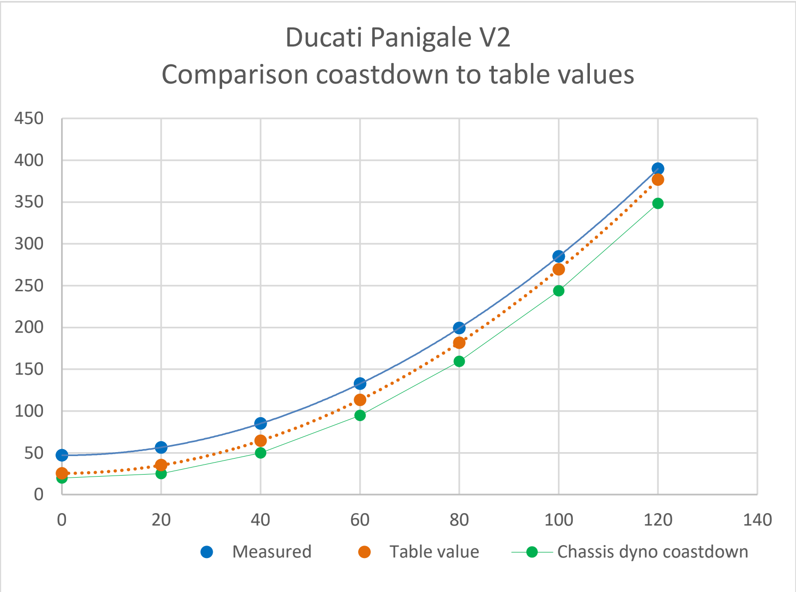

Figure 33 - Comparison of coast-down results, table values and coast-down on the chassis dynamometer values for a Ducati Panigale (Source: IDIADA).

Once the running resistance coefficients were calculated the next step was to set these as target coefficients for the chassis dynamometer. For this purpose, Annex II on Regulation (EU) 134/2014 was applied. Error requirements were narrowed on the recalculation for the Road Load Adaptation

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with the aim of achieving a more accurate setting for the three verification coast-downs. The maximum allowed errors as specified in the regulation were respected, see Table 21.

Table 21: Chassis dynamometer error requirements and verifications

Setting error ε (force)	125 – 45 km/h	45 – 25 km/h	25 – 5 km/h
Adaptation coast-downs	1 %	1,5%	5%
Verification coast-downs	2%	3%	10%

After the adaptation, the new settings were applied to the chassis dynamometer and the coefficients were verified. The running resistances applied at the chassis dynamometer are shown in Figure 34.

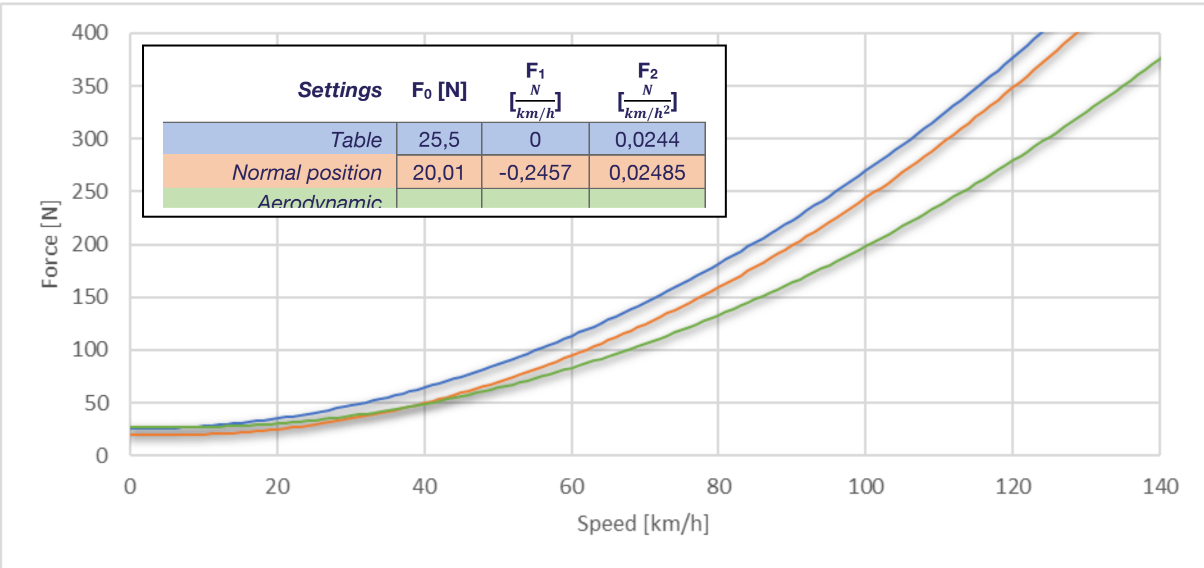

Figure 34: Running resistance as set on the chassis dynamometer for the table values, normal driving position and aerodynamic driving position of the Ducati Panigale V2

When the chassis dynamometer setting procedure was completed, two Type I and Type VII emissions tests were performed with these settings and compared with other tests based on the table values. The results for the CO_2 emissions show there is a small difference for the first phase of the WMTC between the normal and aerodynamic position. This is because the influence of wind resistance is limited at low vehicle speeds. This can be seen in Figure 34, where the running resistance curves are close to one another at low speeds. The CO_2 emission differences for Part II and III are higher due to the higher average speed. These differences in force lead to a gap in the total weighted CO_2 results of ~3% and ~5% respectively for the normal position test and for the aerodynamic position test with respect to the table values test.

The tests at the chassis dynamometer show that for this Ducati Panigale V2 the differences in CO_2 emissions are relatively small between a dynamometer setting according to measured running resistance in the normal position and the table values. However, it should be noted that this difference may be larger for a naked motorbike such as the BMW R1250 and the Yamaha MT-09, as can be seen from the differences between the curves in Figure 29. It would therefore be recommended to perform more coast-down- and chassis dynamometer measurements on different types of motorbikes to get a better understanding of the differences in emissions.

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Furthermore, it was found that the difference in measured running resistance between the normal and the aerodynamic position lead to a small, yet significant difference in CO_2 emissions, particularly for the higher speed points.

7.8 Consequences of real-world running resistances

There is a significant difference between real-world running resistances from the coast-down measurements and the table values for setting the chassis dynamometer, in particular for the BMW R1250 and Yamaha MT-09. However, as explained in paragraph 7.6, this is not directly comparable as the chassis dynamometer resistance is missing. Since this missing resistance is specific to the vehicle and chassis dynamometer used, and the fact that there is no possibility to estimate this missing resistance, the results in this paragraph will unfortunately have to ignore this difference.

The next relevant question then is what the consequences would be for the laboratory-based emission measurements. To obtain a good insight of the differences in emissions, TUG kindly offered to perform simulations with their PHEM model[26]. This model is capable to simulate the engine load and speed second-by-second, based on the vehicle speed and the running resistances. Using generic emission maps, the actual engine load and engine speed is translated into momentaneous emissions, which are integrated over the whole driving cycle into an overall emission value. The BMW and Yamaha MT-09 were simulated using the table value setting, as would normally be the case for a type-approval test, and with the real-world running resistances following from the measurements. This was done for the official type-approval test, WMTC, and for a real-world cycle named 'RDC'. In total, there were 8 simulations performed, see Table 22, where 'RW' is real-world, and 'TV' is table value. Please note that though the PHEM model also delivers output on the pollutant emissions NO_x, CO and HC, these numbers are less reliable than those of the CO_2 emissions, fuel consumption and cycle work, therefore these are presented in grey and should be interpreted as indicative. The Yamaha R7 was not simulated, as the difference between real-world resistances and the table values is only 5%.

Table 22: Overview of simulation results

	Simulation case	**CO_2 [g/km]**	**Fuel [g/km]**	NO_x [g/km]	CO [g/km]	HC [g/km]	**Work [kWh/km]**
BMW R1250 GS	WMTC/TV	141,7	45,4	0,044	0,511	0,090	0,090396
BMW R1250 GS	WMTC/RW	158,7	50,9	0,050	0,573	0,102	0,119618
Difference		*+12,0%*	*+12,0%*	*+15,1%*	*+12,2%*	*+13,1%*	*+32,3%*
BMW R1250 GS	RDC/TV	143,2	45,9	0,047	0,535	0,092	0,097846
BMW R1250 GS	RDC/RW	161,3	51,7	0,054	0,598	0,102	0,126780
Difference		*+12,6%*	*+12,6%*	*+14,4%*	*+11,7%*	*+10,6%*	*+29,6%*
Yamaha MT-09	WMTC/TV	125,8	40,3	0,044	0,512	0,090	0,0819
Yamaha MT-09	WMTC/RW	141,1	45,2	0,050	0,572	0,101	0,1078
Difference		*+12,2%*	*+12,2%*	*+15,4%*	*+11,8%*	*+12,6%*	*+31,7%*
Yamaha MT-09	RDC/TV	126,8	40,6	0,046	0,533	0,090	0,0876
Yamaha MT-09	RDC/RW	143,2	45,9	0,053	0,594	0,100	0,1137
Difference		*+12,9%*	*+12,9%*	*+14,9%*	*+11,4%*	*+10,6%*	*+29,8%*

TV = Table Value, according to Appendix 5 to EU Regulation No 134/2014

RW = Real-World, according to the road-load determination procedure as measured by TNO

The simulation results are generally well in agreement for both motorcycles and the simulated driving cycles. The increase in fuel consumption and CO_2 emissions as a result of the difference between the real-world running

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resistance and the table values amounts to 12 to 13% in all cases. This increase is considerably less than the difference in cycle work, which is about 30 to 32% higher for the real-world running resistance but is still considered substantial. Though this means that there is more fuel needed for driving the vehicle, at the same time the engine operation is moved to areas of the engine map where the efficiency is better. This is why the increase in work is not proportional to the increase in fuel consumption and CO_2 emissions. Also note that the increase in work is lower than the difference in running resistance between real-world and the table values, which may differ by 40 to 78%, depending on the vehicle speed (see paragraph 7.4). The explanation for that is in the energy needed to accelerate the vehicle, which is mainly mass based and therefore the same for both simulated running resistances. Also, when the vehicle is at standstill, the fuel consumption and CO_2 emissions are the same. These factors make that the relatively high differences in running resistances translate into a lower difference of cycle work, and eventually again into lower differences in fuel consumption and CO_2 emissions.

Again, it needs to be stressed that these differences would be lower in reality, as the unknown chassis dynamometer resistance should be added to the table value resistance. In addition, it should be noted that even though CO_2 emissions and fuel consumption are measured by the type I emission test in EU Regulation No 143/2014, there are no CO_2 emission standards in place for L-category vehicles. Nevertheless, the fuel consumption is used as consumer information.

The results of the simulation provide valuable insights, although no conclusions can be drawn due to the incomparability of table values and coast-down results, as explained earlier. Therefore, it is recommended to check these results by measurements on a chassis dynamometer, e.g., by applying higher road loads. As an alternative, a comparative analysis could be made between emissions at specific speeds during the chassis dynamometer tests and during on-road tests.

7.9 Conclusions and recommendations

The results presented in this investigation have shown that there are significant differences between the running resistance measured via the coast-down test procedure on the test track and the table values as presented in Appendix 5 to emissions type-approval EU Regulation No 134/2014, which both are alternatives for setting the chassis dynamometer to perform the type I emission test.

However, these running resistances are not directly comparable. The table values are chassis dynamometer setting values, meaning that the rolling resistance of the motorcycle tyre on the rollers of the chassis dynamometer will add to the resistance that the vehicle experiences. Also, this added resistance will be specific to each chassis dynamometer and depend on the roller diameter and roller surface. For one specific motorcycle there was a comparison made between the chassis dynamometer setting following from the coast-down running resistance and the table values. This showed that the table values are slightly higher. However, since the table values use normalised aerodynamic characteristics, regardless of the vehicle bodywork (only mass is considered), this situation might favour the table values for less aerodynamic vehicle bodies, in particular naked bikes such as the BMW R1250 Adventure and the Yamaha MT-09. This could unfortunately not be verified in this investigation, but it seems likely that a certain benefit for emission type-approval would be present for less aerodynamic vehicles.

It should also be noted that the table values do not correspond to those in place for the emissions type-approval of passenger cars in EU Regulation No 2017/1151. For passenger cars, these values are not chassis dynamometer settings, but target settings. This means that the chassis dynamometer should be set such that the running resistance replicates the resistance as specified by the table values, thereby making the table values directly comparable to the measured running resistance by the coast-down test procedure. More importantly, the effect of tyre rolling resistance on the chassis dynamometer is implicitly compensated for, making results from

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different dynamometers better comparable. Furthermore, the coast-down procedure for passenger car has a number of other aspects that would improve the procedure for L-category vehicles, such as the introduction of an f_1 fitting parameter, smaller speed intervals and corrections for wind.

The main question is whether a difference in running resistance leads to any significant change in emissions from the type I test. Simulations indicate that an increase in running resistance yields a higher CO_2 emission, but much less than proportionally. For the other emission components, the results are not sufficiently reliable.

These conclusions lead to the following recommendations to make the running resistances on the chassis dynamometer better comparable to the actual running resistance on the road. On the basis of the outcomes of that investigation, the table values in Appendix 5 to emissions type-approval EU Regulation No 134/2014 may be converted from a chassis dynamometer setting scheme to a target setting scheme. This will also make the emission results better comparable by reducing the influence of the specific chassis dynamometer. As a consequence, a new set of table values would have to be developed.

1. It is recommended to perform an investigation to quantify the gap between the chassis dynamometer setting from the coast-down test procedure and the tables values for a whole range of on-road motorbike types.
2. For this new set of table values it is advised to ensure these are chosen conservatively, i.e. having a higher running resistance than measured by the coast down test procedure. In this way, an incentive exists for the manufacturer to measure the real running resistance instead of cherry picking for the lowest curve.
3. To account for the (expected) aerodynamic characteristics of the vehicle, it is advised to consider that element in the table value scheme, although this is probably not easy to objectively include. A simple alternative approach is to ensure that the table values are sufficiently conservative, making a coast-down test more attractive, particularly for aerodynamically shaped vehicles.
4. It is recommended to consider applying table values as a target setting instead of a chassis dynamometer setting. Of course, this would mean that a revision of the table values should take this new approach under consideration.[24]
5. The coast-down test procedure is recommended to be evaluated and improved, by taking in elements from the procedure for passenger cars in EU Regulation No 2017/1151 that are currently missing, such as a third fitting parameter f_1 for the running resistance curve, smaller speed intervals and applying a correction for the influence of wind.

[26] Opetnik, Martin, Stefan Hausberger, Claus Uwe Matzer, Silke Lipp, Lukas Landl, Konstantin Weller, and Miriam Elser. 2024. "The Impact of Vehicle Technology, Size Class, and Driving Style on the GHG and Pollutant Emissions of Passenger Cars" Energies 17, no. 9: 2052. https://doi.org/10.3390/en17092052

[24] It should however be noted that the chassis dynamometer setting procedure for target values is more time exhaustive than the current procedure for chassis dyno values

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8 ANNEX II “Czech University of Life Sciences in Prague mobile FTIR system”

Within the LENS project, an FTIR analyser has been extensively modified by the Czech University of Life Sciences and by CreaTech (an engineering and prototyping company), resulting in a highly compact, 70 x 35 x 30 cm, 35 kg package including Michelson interferometer, 5 m path length multi-pass cell, heated sample line, heated filter and pump, with sampling system optimized to achieve a less than 2 s response time (t90). A MCT detector cooled by liquid nitrogen and ZnSe windows have been used to provide 0.5 cm^{-1} optical resolution at 5 Hz scanning rate (analogous with laboratory instruments), while avoiding the need for nitrogen or other gas for the flushing of the optics. Power and thermal management have been thoroughly optimized to achieve a nominal average consumption of around 200 W, and less than 300 W when operating at -9 C. The analyser has been tested at temperatures of -9 to +30 C.

Figure 35: mobile FTIR instrument of CZU (left), installation setup of the mobile FTIR on a L3e-A3 category two-wheeler.

For fast mounting on the motorcycle, an external frame backpack has been fabricated for carrying the FTIR. The backpack is worn by the motorcycle driver, with the mass of the instruments resting on the passenger seat. The mobile FTIR (Figure 35) has been used on various types of mopeds and motorcycles capable of carrying two passengers, including L3e-A1 scooters, L3e-A2 and L3e-A3 motorcycles, L5 tricycles and L7 quads. Its use on L1e mopeds has been found to be feasible on those mopeds that have sufficient weight carrying capacity, however, due to the excessive emissions of lubricating oil from 2-stroke mopeds, measurements were not done to avoid contamination of the optics with oily deposits, which would create artefacts for subsequent measurements and require a relatively complicated cleaning of the sampling system.

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