L-vehicles Emissions and Noise mitigation Solutions

D6.5
Recommendations for quieter and cleaner LVs

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Executive summary

The LENS project represents a three-year European Union funded research initiative with the purpose of developing evidence-based recommendations for reducing pollutant emissions and noise from L-category vehicles. Through comprehensive methodologies and use of advanced measurement technologies developed during the project, including real-world and laboratory testing of 150 vehicles, three roadside measurement campaigns in three European countries, several technical inspections of vehicles for tampering detection, and extensive user surveys, the project has established a robust foundation for supporting future European policy initiatives and mitigation measures. Measurement results feed into the development of updated emission factors, ensuring accurate environmental impact assessment. This methodology is designed to deliver practical solutions for current vehicle fleets while informing future regulatory frameworks, guiding policymakers, municipalities, and industry stakeholders toward effective strategies for reducing both noise pollution and air emissions from L-category vehicles across all operational conditions from real-world environments, contributing to more sustainable mobility solutions.

The investigation has revealed significant discrepancies between type-approval test conditions and real-world operation across all L-category sub-categories. Pollutant emissions measured during real driving conditions substantially exceed homologation values, especially for some of the low-powered vehicles. Critical emission events include cold starts, high-engine-load operation, and dynamic acceleration scenarios. These all conditions are inadequately represented in current regulatory frameworks. Similarly, noise measurements demonstrate that real-world sound pressure levels frequently exceed homologation limits during typical urban operation, with current type-approval procedures failing to capture high-noise transient events characteristic of everyday use.

LENS employs cutting-edge portable emission measurement systems (mini-PEMS) and smart emission measurement systems (SEMS) specifically adapted for L-category vehicles. The methodology extends to PN10 and PN2.5, providing insight into ultrafine particle emissions. Roadside inspection campaigns in three cities enable the screening of more than 2,000 to identify tampered or high-emission vehicles in real traffic conditions.

Vehicle tampering represents another substantial challenge identified. A significant percentage of inspected vehicles showed modifications to exhaust systems, engine control units, and air intake systems, primarily motivated by power enhancement and sound preferences. These modifications substantially increase both emissions and noise levels, undermining regulatory efforts to protect environmental quality and public health.

For cities and citizens, our findings support implementing Low Emission Zones with the focus of identifying high-emission L-category vehicles in densely populated areas, complemented by automated enforcement systems. Public awareness campaigns can foster community support while encouraging drivers to more environmentally conscious driving behavior and proper vehicle maintenance.

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Enforcement authorities should implement mandatory periodic technical inspections specifically designed to detect common tampering methods, complemented by effective roadside checks and strengthened market surveillance to restrict the availability of non-compliant replacement parts.

For regulators, type-approval procedures must be comprehensively updated to include a wider range of operating conditions that better represent real-world vehicle use, establishing limits for currently unregulated emissions and revising the vehicle classification system to ensure appropriate test driving cycles and requirements are applied to each L-vehicle subcategory. At same time, manufacturers should optimize emission control systems for wider operating ranges and accelerate the transition to electric propulsion technologies.

The proposed strategic intervention areas of improving type-approval regulations, reducing vehicle tampering, enhancing driving behavior, implementing access restrictions, and accelerating fleet renewal all demonstrate positive benefit-cost ratios for the 2025-2050 period. By addressing both technological and policy dimensions, this comprehensive approach offers a balanced pathway toward a significative reduction of the environmental impact of L-category vehicles while still offering this mobility solution for European citizens in a greener and quieter ecosystem for future generations.

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List of abbreviations

Abbreviation	Name
ASEP	Additional Sound Emission Provisions
CBA	Cost Benefit Analysis
CITA	International Motor Vehicle Inspection Committee
CVS	Constant Volume Sampler
CVT	Continuously Variable Transmission
ECU	Engine Control Unit
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust Gas Recirculation
FTIR	Fourier-transform infrared spectroscopy
LV	L-Category Vehicle
NGO	Non-governmental Organization
OEM	Original Equipment Manufacturers
PC	Passenger Car
PEMS	Portable Emissions Measurement System
PHEM	Passenger car and Heavy-duty Emission model
PI	Positive Ignition
PM	Particle Mass
PMR	Power to mass ratio
PN	Particle Number
PTI	Periodic Technical Inspections
RDC	Real Driving Cycle
RDE	Real Driving Emissions
SEMS	Smart Emissions Measurement System
SPN	Solid Particle Number
VIN	Vehicle Identification Number
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WMTC	World Motorcycle Test Cycle
WP	Working Package

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1 Introduction

This document serves multiple stakeholder communities, reflecting the multifaceted nature of sustainable urban mobility challenges. The recommendations are specifically tailored for cities and citizens seeking to improve urban livability, enforcement authorities responsible for regulatory compliance, policymakers and regulators developing future standards, vehicle drivers making informed mobility choices, and Original Equipment Manufacturers (OEMs) developing next-generation cleaner and quieter vehicle technologies.

This document represents the final deliverable D6.5 “Recommendations for quieter and cleaner Light Vehicles” of the LENS project, a three-year research initiative funded by the European Union designed to address environmental challenges posed by L-category vehicles in real-world environments.

The primary objective of this document is to provide evidence-based recommendations for reducing both noise and pollutant emissions from current and emerging light vehicle technologies, synthesizing the extensive research and data collection conducted throughout the LENS project.

The findings are organized to deliver a detailed analysis of exhaust and noise emissions characteristics, and tampering impact assessment, followed by strategic intervention areas with specific guidance for each stakeholder group (cities, enforcement authorities, regulators, riders, and manufacturers). Throughout the document, we maintain focus on practical implementation pathways supported by cost-benefit analysis.

This integrated approach seeks to enhance regulatory frameworks, enforcement mechanisms, and vehicle technologies to support the transition toward improved environmental quality and sustainability in Europe, while ensuring access to efficient transportation options.

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2 LENS findings and results

The following section presents the comprehensive findings derived from the LENS project's extensive research activities. These findings encompass critical insights obtained through real-world testing data of noise and emissions from L-category vehicles, providing valuable data on actual performance under real-driving operation conditions. Additionally, the results identify the gaps and proposal for revisions to both exhaust emission testing procedures and noise emission measurement protocols, with the purpose of enhancing the accuracy and reliability of current regulatory frameworks. Furthermore, this section details the development and validation of advanced detection techniques specifically designed to identify tampered L-category vehicles, addressing a significant gap in current enforcement capabilities. Collectively, these findings contribute to a more comprehensive understanding of L-category vehicle performance and provide the foundation for improved regulatory approaches and enforcement strategies.

2.1. Requirements for LENS test program

An investigation was made into the driving conditions of L-category vehicles that are relevant for high noise and pollutant emission events [1]. This included:

- Review of existing knowledge on real world driving conditions from previous projects, WMTC development, manufacturer data and the public domain. Several datasets were analysed.
- Identification of L-vehicle operation and critical driving conditions for noise and emissions.
- Targeted roadside/on board measurements to validate preliminary findings on critical cases.
- Assessment of the extent that current type approval regulations cover real world driving conditions.

It was recommended to include the identified driving conditions in the LENS test programme – where possible –, including on-road, test track and/or lab measurements. In-use vehicles representative of the EU27 fleet, with a mileage of at least 3000 km, were recommended to be selected.

An overview of UN regulations for noise and emissions was provided, together with fleet characteristics. A list of critical conditions for high noise events was identified, listed in Table 2-1, based on earlier roadside measurements of regular traffic at several urban locations, and validated in a new set of measurements in the city of Utrecht. Several conditions were identified that can cause high noise emissions, but which are not covered by the type approval regulations, which focus more on average driving conditions.

Engine speed is the predominant influence parameter for noise, followed by engine load. Any test procedure intended to identify high noise events should therefore take these parameters into account.

For exhaust emissions, it was recommended to include the identified high emission conditions in the tests for a certain number of vehicles, ideally during on-road measurements by using Smart Emissions Measurement System (SEMS) or Portable Emissions Measurement System (PEMS) devices. Similar to noise, several of the recommended conditions are not covered by the current TA test procedures.

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However, for emissions it was recommended to implement these conditions in the driving cycle (ideally on-road testing), rather than for roadside measurements which are difficult to measure the whole dynamic effects. The most important conditions with potential elevated emissions are listed in Table 2-1.

Table 2-1: Recommended driving conditions for the noise and emission test program, ordered in possible test sequence

Condition	Vehicle operation	Short name	Already in noise TA?	Noise Remarks	Already in emission TA?	Emission Remarks
(1) Cold start (mainly for emissions)	Engine start	'coldstart'	No		Yes	Emission budget?
(2) Speed (rpm) burst	Stationary, short activation and release of accelerator	'rpmburst'	No	From idling, 3× 50% max rpm	No	From idle, 3× 50% max rpm
(3) Acceleration from standstill, G1, G2 Loaded + unloaded	Acceleration, late gear change	'rpmlongacc'	No		Partly	
(4) Max rpm pass-by esp. mopeds, scooters, sports MCs	Constant speed with max rpm	'rpmconthi'	No		No	Mopeds: Wide Open Throttle
(5) Transition from constant speed or acceleration phases to deceleration phases	Deceleration	'rpmdropoff'	No		Partly	
(6) 'Max' acceleration from standstill, G1, G2	Acceleration	'rpmshortacc'	No		No	Sportive and dynamic driving
(7) Acceleration at speed, from 50 to 100 km/h	Acceleration, may be varied	'rpmmidspeedacc'	MC: ASEP no, RD-ASEP yes		No	
(8) rpm fluctuation	Variable speed	'rpmfluct'	No	Accelerator intermittent	No	Accelerator intermittent – dynamic driving
(9) Backfire (occurrence, distance not critical)	Multiple gear changing or manual operation	'bang'	No for R41.04. R41.05 measurement covers deceleration phase	Condition at which backfire would be most likely	No	Condition at which backfire would be most likely

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2.2. L-vehicle exhaust emission measurements

Comprehensive evidence-based findings on driving patterns for emission assessment of L-category vehicles, derived from an extensive measurement campaign totaling 150 vehicles have been developed. The analysis characterizes pollutant emission performance for a variety of TA and real-world operating conditions, including high accelerations, speed variations, high-speed operation, etc.—conditions frequently not included in current type-approval procedures. This research represents a significant methodological progression in quantifying real-world L-category vehicle emissions through comprehensive assessment across multiple regulatory sub-categories. Based on these findings, the project provides recommendations for improving type approval procedures to ensure reduction of exhaust gas and noise emissions. This encompasses the identification of weaknesses in current type approval methodologies, the evaluation of possibilities to incorporate real driving emission testing within the TA procedure, and the assessment of both suitability and technical readiness of measurement instruments for emission testing under these enhanced conditions.

2.2.1 Real-world operation events to assess exhaust emissions

This investigation represents a significant methodological progression in quantifying real-world L-category vehicle emissions through comprehensive assessment across multiple regulatory sub-categories [2]. Operational driving patterns in real-world conditions demonstrate fundamental deviations from standardized laboratory environments, including dynamic speed profiles, non-steady-state acceleration and deceleration events, and diverse traffic conditions that cannot be adequately characterized in laboratory testing protocols and are frequently occurring in real-world driving patterns.

Upon comprehensive data assessment, the investigation identified carbon monoxide (CO) as the most critical emission component, exhibiting significant mass increases during high engine load operation. Hydrocarbon (HC) emissions demonstrated comparable behavioral patterns but with reduced magnitude. On the other hand, nitrogen oxides (NOx) are not a major problem for gasoline vehicles and also demonstrated low sensitivity to high emission events, generally maintaining compliance with TA regulatory thresholds, this is not the case for diesel L-Category vehicles.

Finding 1: Cold-Start phases, defined as approximately the initial 100s of vehicle operation, have an important impact on pollutant emissions.

- Engine thermal conditioning during the warm-up phase results in sub-optimal combustion efficiency and temporarily ineffective emission aftertreatment systems. These conditions generate significantly high emissions.
- The cold start phase leads to significantly higher emissions, particularly for the components CO and HC [1]. The increase for CO ranges from 4.3[2] and 8.1[3] times the warm emissions, while HC emissions are at least 13.4[3] times higher. Regarding NOx and Particle Number (PN) the emissions increases range between 2.3[3] and 6.0[2] times for NOx, and approximately by 3.0[3] times for PN.

[1] Cold start emissions assessment has been developed considering emissions measured in mg/s, as it has been considered the most representative unit for this specific event.
[2] Value obtained through an analysis with a dataset containing vehicles from all emission standards and only on-road measurements with prototype equipment.
[3] Value obtained through an analysis with a dataset containing only Euro 5 vehicles and on-road and chassis dyno measurements.

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Finding 2: High engine load and/or vehicle speed conditions are especially severe for low-powered L-Category vehicles, as their typical real-world operating points are not covered by WMTC.

- Real-world operational conditions require vehicle operation at high engine loads and speeds, exceeding those prescribed in TA protocols. Low-powered motorcycles exhibit disproportionate sensitivity to these conditions, as they frequently operate at or near maximum design speed and power output operational state, which are not adequately represented in current TA testing frameworks.
- L3e-A1 vehicles commonly operate at their maximum design speed, thus requiring maximum power output. Similarly, low-powered L3e-A2 vehicles equipped with Continuously Variable Transmission (CVT) frequently operate at their rated power. Both vehicle types exhibit substantially elevated CO and HC emissions, under these operating conditions, see Figure 2-1, primarily because they operate outside their designed normal usage conditions and under driving patterns significantly different from those required by TA.
- High-power motorcycles demonstrate considerably more consistent emission performance across several operational conditions evaluated, which try to cover as much of real-world driving behaviour as possible. Measuring high-performance motorcycles at high engine loads is challenging (tyre slip, equipment carried by the vehicle, etc.) and it is particularly demanding to have a reliable picture of how they perform under sporty conditions. Specific L3e-A3 vehicles exhibited exceptionally elevated NOx emissions when operated above their designated WMTC maximum speed, demonstrating a rather inefficient emission control. Proper emissions control is required to ensure adequate level of NOx emissions over a wider operation range than what is currently covered by TA conditions.
- Particle Number shows increased emission values during high-speed operation and acceleration events, and these conditions are the main contributor to overall PN emissions.

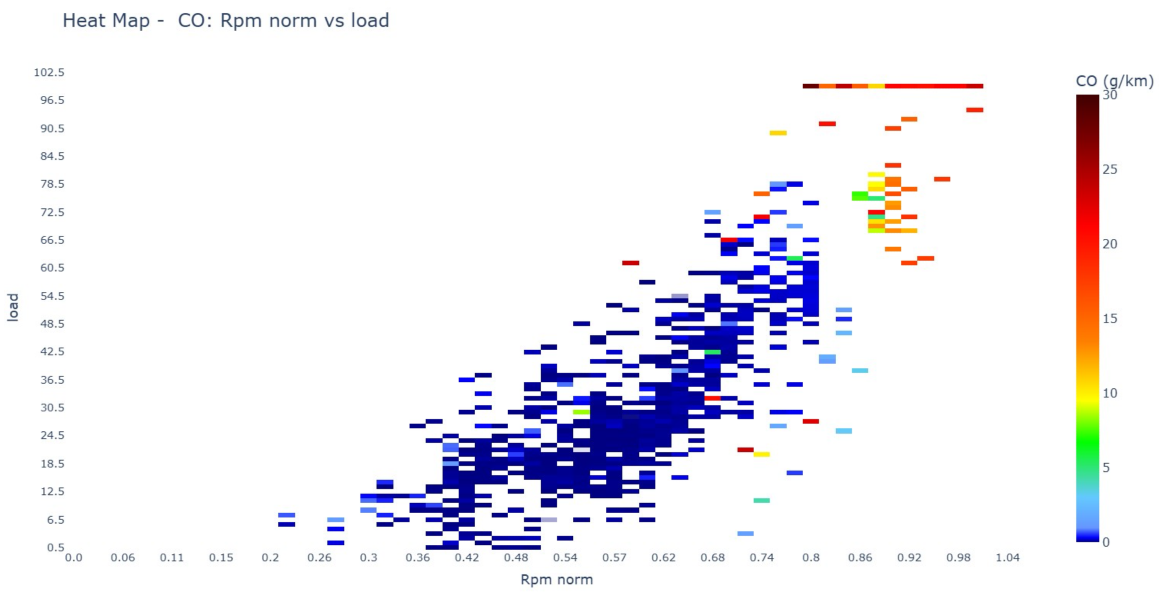

Figure 2-1: CO hot emissions in (g/km) of low-powered CVT L3e-A2 vehicles, under real-world driving conditions. Data represented against engine load (%) and normalized rpms (nr).

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Finding 3: Maximum Engine Speed (rpm) is another major contributor of high emissions, following the same patterns as high engine load.

- Maximum engine speed emissions analysis has been focused in L1e-B sub-category, since these vehicles have reduced performance and are driven at maximum engine and vehicle speed, without necessarily accelerating. L3e-A1 and low powered L3e-A2 also operate under these conditions, but not at such a high frequency as the previous ones.
- Four-stroke mopeds emission performance is little affected by speed, as maximum speed events are included in the WMTC Class 1 cycle, so there seems to be satisfactory control of their emissions.
- L3e-A1 and low-powered L3e-A2 vehicles equipped with CVT frequently operate at maximum engine speeds and exhibit significantly elevated emissions under these driving conditions.
- High-powered motorcycles are difficult to test close to maximum engine speed, and such conditions are not very frequent, especially in urban traffic.

Finding 4: Acceleration from 50 to 100 km/h events represent significant emission increases across all measured pollutants.

- This operational condition represents a notable high-emission scenario particularly relevant to real-world driving patterns, frequently encountered in urban-to-rural transition zones and highway access.
- All emission components are affected by this specific event, with an average increase of 1.7 and 2.6 times [2] compared to overall HC and NOx emissions. Severity is higher in this specific event for CO emissions, with an average increase of 3.5 times [2].

Finding 5: Maximum Acceleration events represent an increase across all regulated pollutants.

- This operational condition, characterized by maximum throttle application and rapid velocity change, represents a significant high-emission scenario in real-world driving.
- All measured pollutants (CO, HC, NOx) demonstrate increased emissions compared to overall emission values by 2 times for NOx, 2.5 for CO and 8.4 for HC[2].

Finding 6: Less relevant driving conditions for the TA test framework

- Aside from the driving conditions mentioned in the previous findings, there were two other driving events hypothesized to result in excess exhaust emissions, namely the acceleration from standstill and the transition from constant speed or acceleration phase to deceleration. Though there were emission increases observed, especially for the acceleration from standstill, these remained below an increase of 50% with respect to the warm emissions. Therefore, these conditions are less relevant to be considered for the TA test.

Finding 7: Current regulatory frameworks assign L3e-A1 vehicles to either WMTC Class 1 (same as mopeds) or Class 2-1.

- According to Regulation (EU) 134/2014 (Annex II, Figure 1-1), all vehicles with engine capacity under 150 cc and maximum speed under 100 km/h belong to WMTC Class 1. Consequently, both mopeds and those L3e-A1 motorcycles whose maximum speed does not exceed 100 km/h are certified following same criteria, a driving cycle including only urban driving with a maximum speed reaching only 50 km/h. This classification distinction for the specific L3e-

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A1 vehicles results in substantially elevated emissions during Real Driving Cycle (RDC), as most real-world operating points are not covered by WMTC Class-1.

- Regarding L3e-A2 vehicles, classification into WMTC Class 2-1, 2-2, 3-1, or 3-2 depends on maximum achievable vehicle speed, with substantial differences between test cycles. WMTC Class 3-2 coverage for these vehicles extends to higher engine speed regimes and velocities, demonstrating appropriate correlation with both on-road measurements and RDC parameters regarding engine operating map coverage (see Figure 2-2) For WMTC Class 2-1 vehicles, speed coverage remains below 85 km/h, while Class 2-2 extends only to 95 km/h, demonstrating an important discrepancy with actual real-driving behavior. WMTC Class 3-1 vehicle speed coverage reaches 110 km/h, which better represents the real-world driving conditions typically encountered by low-powered L3e-A2 motorcycles

Finding 8: L-Category vehicle Type Approval (TA) driving dynamics ($v*a_{pos}$ metric) significantly underestimates actual driving behavior observed in real-world driving conditions, especially for L3e-A2 and L3e-A3.

- Regarding TA procedures, both L-category vehicles (WMTC) and passenger cars (WLTC) exhibit remarkably similar driving dynamics values, which clearly demonstrates that current TA regulation is not appropriately adapted to the actual real-world driving conditions of L-category vehicles.
- As a reference point from established legislation with extensive implementation history, RDE measurements on passenger cars demonstrate timid increases in driving dynamics ($v*a_{pos}$) compared to the WLTC, with only 15% and 25% higher values for the rural and highway phases, respectively.
- For L1e-B only urban phase applies, and $v*a_{pos}$ values are 10% greater than TA.
- Regarding L3e-A1, those vehicles classified in WMTC Class 1 have shown $v*a_{pos}$ values greater by 70% than the urban WMTC phase, the only one covered by TA. On the other side, L3e-A1 vehicles classified as WMTC Class 2-1 have shown $v*a_{pos}$ values greater by 25% and 70% for the urban and rural phases, respectively. No highway driving conditions are covered by TA.
- For the L3e-A2 and L3e-A3 sub-categories, real-world measurements have shown that $v*a_{pos}$ values are approximately 10 - 20%, 60% and 90% greater, respectively for the urban, rural and highway phases, compared to WMTC. These substantially elevated values provide clear evidence that current TA regulatory protocols underrepresent the actual dynamic driving characteristics that L-category vehicles experience in real-world operation.

Finding 9: Power-to-mass ratio (PMR) shows very high values for L3e-A3 and high powered L3e-A2, considerably higher than for Passenger Cars (PCs)

- Excluding L3e-A3 vehicles, the vast majority is condensed under the average value of 0.2 kW/kg. L3e-A3 vehicles are highly powered, with PMR values which are about to hit 0.8 kW/kg, nearly 400% times the maximum typical value for passenger cars. An average family car is near 0.07kW/kg, and a hyper car up to 0.25 kW/kg.
- These vehicle characteristics reflect that the driving scenarios to which L-category vehicles are subjected present not so many similarities with passenger cars. This evidence clearly demonstrates that the dynamic capabilities of L-category vehicles are unique and strongly dependent on the subcategory. L-category vehicles cover a wide range of vehicle

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characteristics and therefore must be evaluated through specifically designed protocols rather than adapted passenger car methodologies.

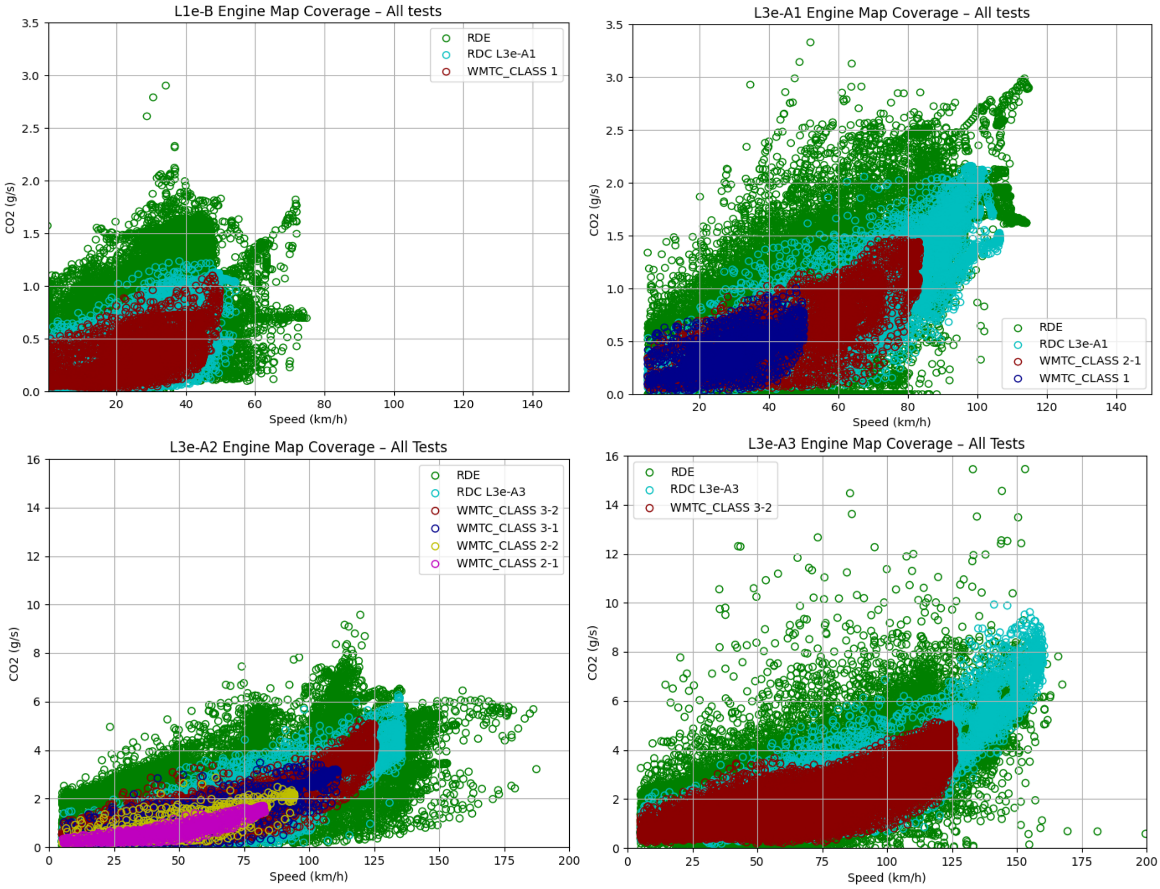

Figure 2-2: L1e-B (top-left), L3e-A1 (top-right), L3e-A2 (bottom-left) and L3e-A3 (bottom-right) engine map coverage for all the measurements performed, distinguished by TA test type (WLTC Class), RDC and on-road (RDE). CO2 (g/s) against vehicle speed in (km/h) is represented.

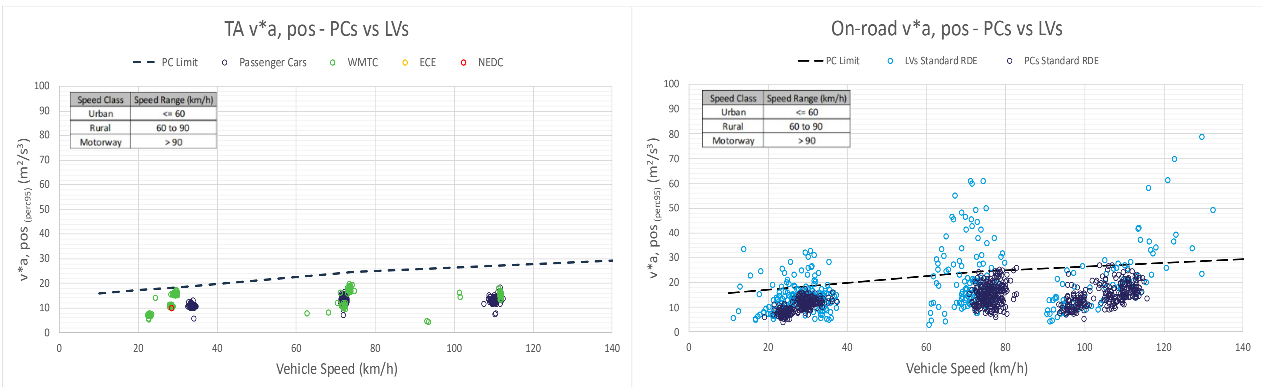

Figure 2-3: Driving dynamics v*a, pos comparison between Passenger cars and L-Category vehicles within TA and on-road (RDE) measurements.

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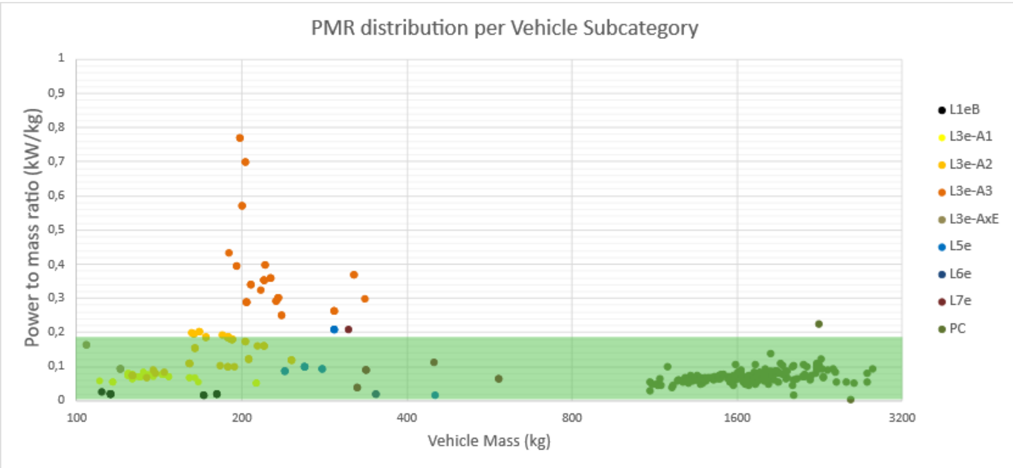

Figure 2-4: Power-to-mass ratio (PMR) distribution of the vehicles measured in LENS db per subcategory. Additionally, more than a total of 100 Passenger Cars from GreenNCAP PMR values are represented.

Finding 10: 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 of Euro 5 vehicles is below the limit values when vehicles are tested over the WMTC test procedure. Only the mopeds category (L1e-B) and Enduro motorcycles (L3e-AxE) showed considerably higher CO and HC values, whereas a diesel (L6e-B) showed much higher NOx emission.
- Over the RDC driving pattern conducted in the lab, representing real-world conditions, almost all sub-categories exceeded both the CO (see Figure 2-5) and NOx limits (see Figure 2-7), and the L1e-B vehicles considerably also exceeded the HC limit[4] (see Figure 2-6).
- 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 [4].

CO emissions

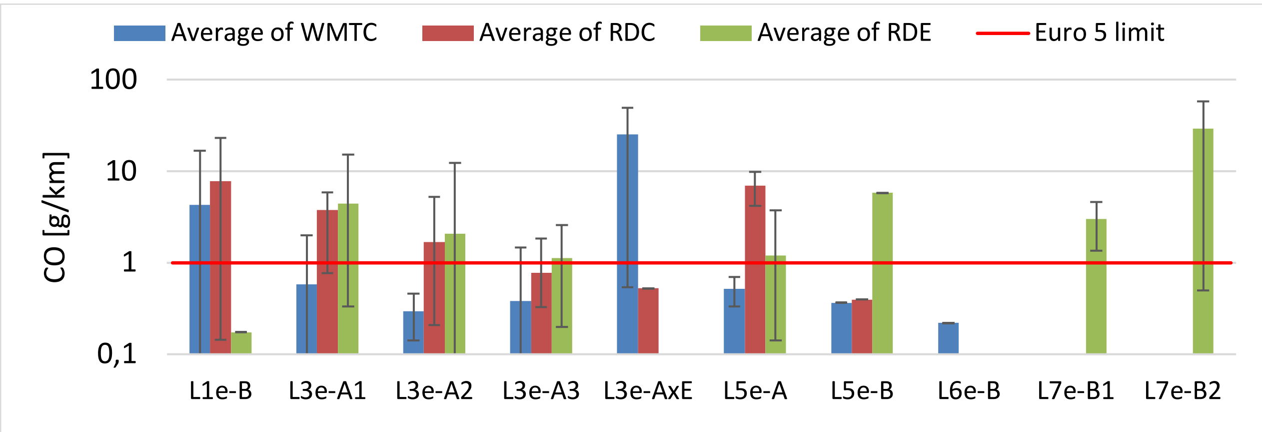

Figure 2-5: Average CO emissions per category and type of test including standard deviations.

[4] It has to be noted that no phase weighting has been applied to these measurements.

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HC emissions

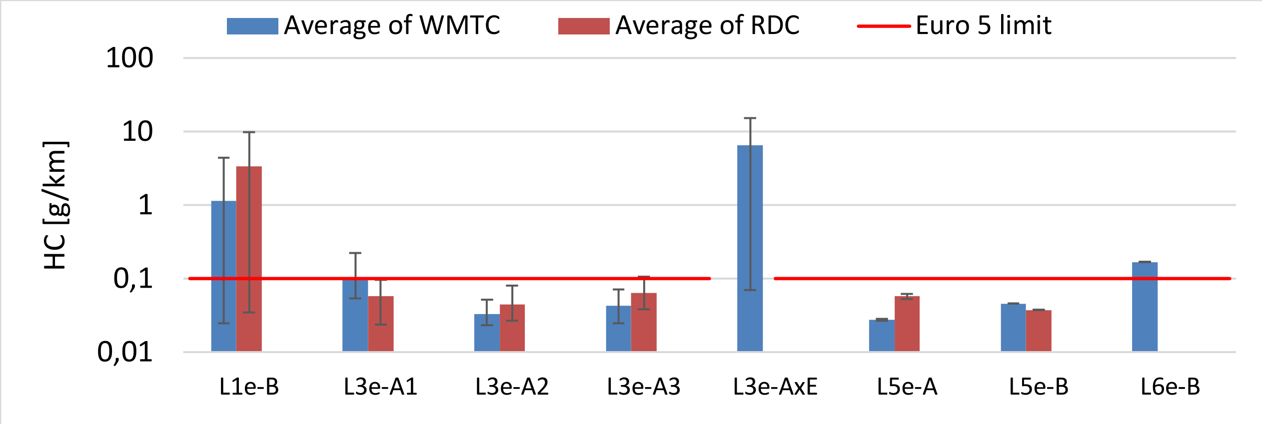

Figure 2-6: Average HC emissions per category and type of test including standard deviations[5].

NOx Emission

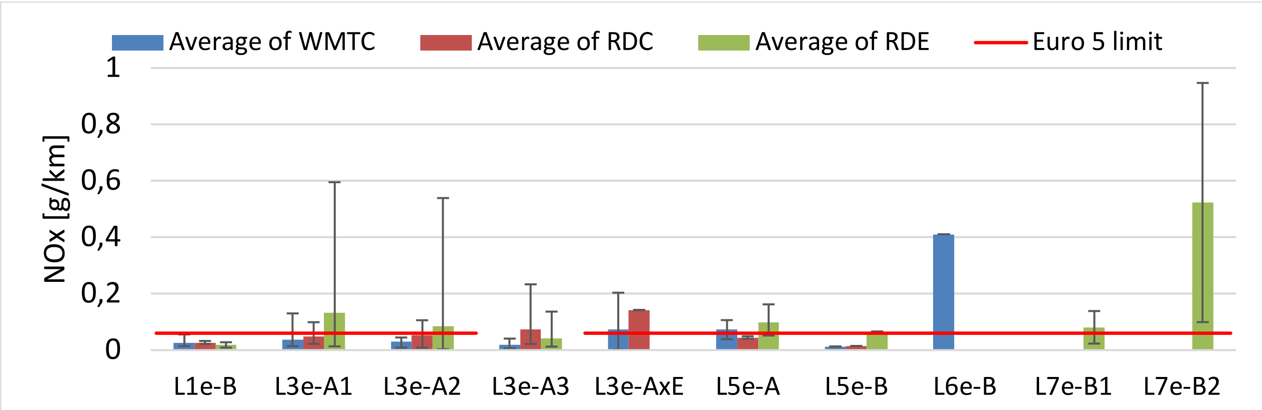

Figure 2-7: Average NO_x emissions per category and type of test[5].

Finding 11: In EURO 5 vehicles, non-regulated pollutants, including particle number (PN), particulate mass[6] (PM), and the non-regulated ammonia (NH_3) and Black Carbon (BC) species exhibited high levels. In several cases, PM and PN were found above the limit of the current passenger car regulation. CO_2 emission increases with engine capacity and power and tend to increase from WMTC to RDC and RDE.

- For the WMTC test all 2- and 3-wheeler show low levels of NH_3, 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 show also increased levels of NH_3 emission.
- 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, despite L-vehicles are port-fuel injected ones and hence no PN limit applies to them, see Figure 2-8.

[5] L3e-AxE is limited with HC + NOx.
[6] Regulated only for CI and PI Direct Injection engines

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- Similar to PN, measurable levels of BC were observed in the few Euro 5 vehicle tests conducted. It is the first time that BC from L-category vehicles is determined in on-road tests. The initial findings suggest that BC should be further studied in future research campaigns.
- PM emissions exceed in several cases the EURO 6 passenger car limit.

PN Emission

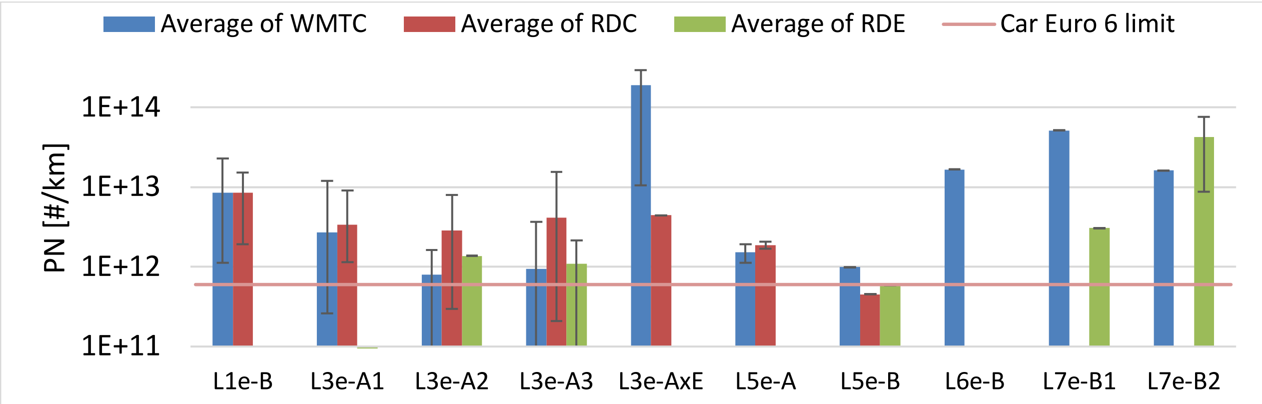

Figure 2-8: Average PN emissions per category and type of test.

Finding 12: Emission levels seem to be significantly violated by specific L-vehicle categories and technologies

In addition to the previous conclusions, that refer to typical emission levels of the so-called average vehicle fleet, there are specific alarming findings for specific vehicle categories / types:

- Two-stroke engines (in smaller numbers) have made it to Euro 5 and present distinctively degraded emission performance compared to their four-stroke ones. From a technical perspective, reaching the Euro 5 limits with small capacity (i.e. 50 cc) two-stroke engines seems infeasible, so still having such vehicles in the market indicates a rather loose type-approval procedure.
- Diesel engines for L6e microcars are still used at Euro 5. Without having exact statistics, the presence on the road of such vehicles is rather limited so the overall environmental burden should be low. Similar to two-stroke engines, it is not considered technically feasible (or at least cost-effective) to reach Euro 5 emission levels with small diesel engines so it is a question how such engine types have made it to the market at Euro 5.
- Less common vehicle models, such as L5e/L7e and special-purpose (e.g. enduro/trial) motorcycles exhibit vehicle specific emission performance. Perhaps owed to their small numbers or the fact that some of these vehicles may also be type-approved in the T-category (agricultural tractors), it could not be excluded that some of these vehicles enter the market with a questionable type-approval procedure.

Finding 13: High impact of obvious vehicle tampering on pollutant emissions

- For some Euro 5 specific vehicles, a tampering impact assessment could be developed as they have been tested both obviously tampered and non-tampered under both TA, RDC and on-road measurements. Usual purpose of tampering is to increase vehicle power, which is achieved by fuel-enrichment strategies, CO and HC are consequently increased, whereas NOx not influenced or even slightly reduced.

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- CO was identified as the most affected pollutant, increasing the emissions by 11 times on average, followed by HC, with an increase of 3.5 times and the NOx, which emissions are reduced by 0.95 times on average.

2.2.2 Suggested revisions to exhaust emissions TA procedure

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 [4]. Out of these insights 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, which should include all of the identified high emission events in a representative way. This can be done either by introducing a full on-road RDE test, which should not pose a significant challenge for larger vehicles, or a real-world driving pattern in the lab. In the latter, more realistic running resistances should also be introduced. Any of these actions requires further development for determining the exact specifications of the proposed changes.

Recommendation 2: Standardized and commercially available measurement equipment for on-road tests is suitable for vehicles with larger 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.** For such small vehicles, the accurate measurement of exhaust flow – especially during on-road tests – is an additional challenge.

Recommendation 3: 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 (such as Black Carbon) should be better controlled. It is therefore recommended to include at least PN and NH_3 in the components covered by the type approval procedure.

Recommendation 4: 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 5: 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 Fourier-transform infrared spectroscopy (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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2.3. L-vehicle noise emission measurements

Due to an additional measurement campaign for noise, which covered over 150 vehicles, evidence-based insights into the noise-relevant driving patterns of L-category vehicles have been generated. The collected data provides a detailed picture of how noise emissions evolve under a broad range of operating conditions, capturing behaviors that extend far beyond those typically reflected in current type-approval (TA) testing. High load demand, abrupt accelerations, fluctuating speeds, high-speed cruising and cold-engine operation were all shown to contribute substantially to real-world noise profiles, often in ways not evident from standardized tests. By systematically analyzing these conditions across multiple LV subcategories, the project establishes a more realistic understanding of noise generation mechanisms and their variability in everyday traffic environments.

2.3.1 Real-world operation events to assess noise emissions

The LENS project aimed to characterize noise emissions from L-category vehicles (LVs) under real-world operating conditions, working under the hypothesis that existing type-approval (TA) procedures do not fully represent noise behavior during actual use. To address this gap, the project developed and validated an on-board measurement system that reached Technology Readiness Level (TRL) 7, consisting of a compact microphone unit and data recorder capable of synchronizing sound pressure level measurements with GPS position, speed, and acceleration data [3].

A total of 14 different LVs across Europe were equipped with this system. The primary focus was to evaluate patterns producing high noise levels that contribute to community annoyance. Measurements revealed that high acceleration phases, aggressive throttle inputs, and rapid deceleration were the most prominent contributors to elevated sound pressure levels. The on-board recordings showed that certain driving patterns produced sound pressure levels significantly above current type-approval (TA) limits for the respective vehicle classes, as represented in Figure 2-9, where the green line shows vehicle speed, whereas the dark curve shows the sound pressure level. Nevertheless, the high values reaching levels up to 97 dB indicate that even at TA measurement distance, the limit values are still surpassed [2].

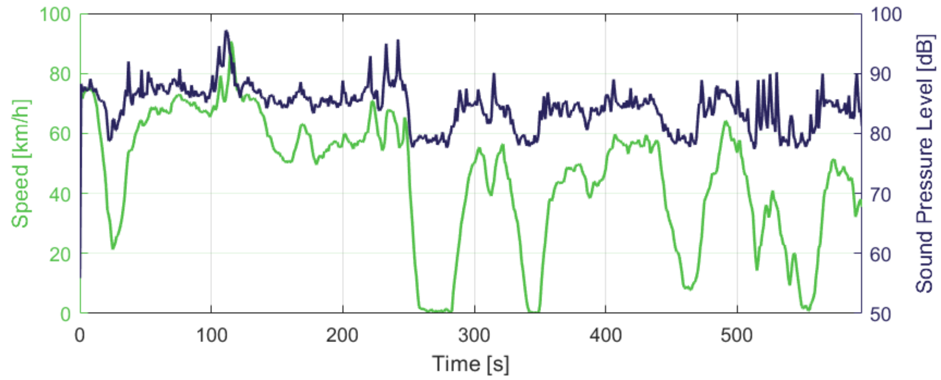

Figure 2-9: On-board measurement system results for one LV for around 10 minutes.

Notable variations in noise emissions were observed even within single vehicle categories despite identical regulatory limits, highlighting the influence of driver behavior and vehicle configurations. Although higher engine performance generally correlated with increased noise levels, this relationship proved not strictly linear, as some lower-performance vehicles produced similar or higher noise peaks

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under certain driving conditions. These results highlight a regulatory gap between TA compliance and actual in-use noise behavior.

To ensure greater comparability with TA conditions, specific driving situations recorded in real traffic were replicated on an acoustic test track, following the specific real-world test, created within LENS project. These real-world driving patterns were tested using over 100 LVs across various L-category subtypes. The controlled environment testing confirmed that higher vehicle speeds and engine loads systematically lead to greater noise emissions [2]. However, the differences between moderate and high acceleration maneuvers were significant, often exceeding TA limits by several decibels, with some maneuvers even exceeding the limits defined in the ASEP procedure.

These findings highlight a clear regulatory gap between TA compliance and real-world noise emissions. The variability within the same type of maneuver was considerable, reflecting the wide range of real-world driving styles and conditions. These observations underline that simple limit reductions in regulatory operating conditions may not effectively address the high-noise events most relevant for public annoyance [5], suggesting the need for test procedures that better capture the real-world driving patterns generating the highest noise levels.

This activity therefore focused on analyzing the real-world driving patterns on an acoustic test track, comparing them to TA procedures, and conducting complementary laboratory analyses to better understand the origin of noise emissions and the effectiveness of current regulatory test methods. Initially, the TA procedure was replicated and sound levels were measured on several vehicles. The results can be found in Figure 2-10, where the final value of the TA (L_{urban}) is shown over the type approval limits. A grey 1:1-line cuts the data into two areas: the one above the 1:1 line shows vehicles which exceed the limit value and the area below the 1:1-line shows LVs being within the limits. This 1:1 line is increased by 1 dB(A) because the tested vehicles were received in an as-is condition, therefore not necessarily being in the conformity of production status, which the testing vehicle must fulfil when type approved. The goal of doing this measurement campaign was to test the reproducibility and robustness of acoustic TA measurements. As some vehicles are above the 1:1-line, the high sensitivity of this procedure becomes clear. Factors like the gear selection that is not specified in TA, the tires type and condition, or overall vehicle condition may have a substantial influence on the test result.

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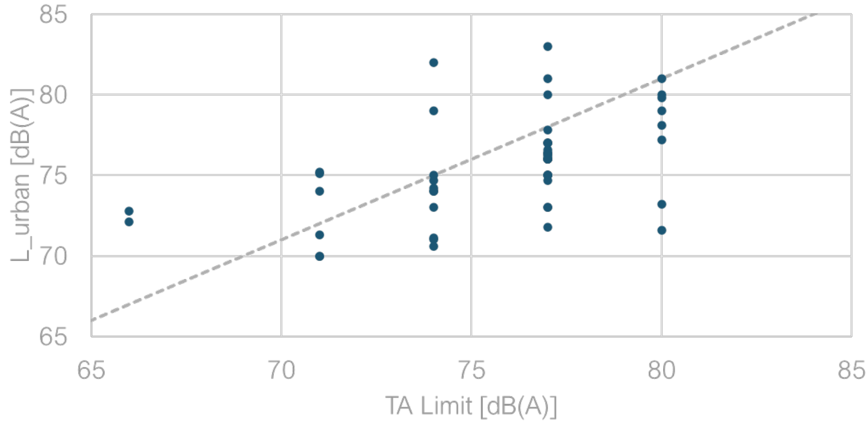

Figure 2-10: Comparison on measured TA sound level and corresponding TA limit.

Finding 1: Real-world noise emissions of L-category vehicles are significantly higher than those measured under type-approval conditions. The on-board measurement campaigns (example shown in Figure 2-11) demonstrated that many real-world driving situations generate sound pressure levels far above the values obtained in TA tests. While TA procedures capture only a narrow and simplified range of operating conditions, the recorded in-use data showed that typical traffic maneuvers—including high accelerations, rapid throttle inputs, and transient engine speed changes—produce substantially higher noise levels. The comparison of on-board and standardized TA-derived maneuvers confirmed that several L-category vehicles exceeded the TA-relevant noise thresholds by several decibels when reproducing real-world patterns on the test track (compare to Figure 2-12).

- This trend was visible across multiple vehicle subcategories and was particularly pronounced for maneuvers reflecting dynamic and rider-aggressive behavior. Large intra-category variability was observed, meaning that even vehicles subject to identical TA limits emitted markedly different noise levels in real traffic.
- In several cases, lower-performance vehicles produced unexpected noise peaks under certain real-world conditions, underlining that TA procedures do not sufficiently capture the diversity of genuine riding behaviour or its acoustic implications.

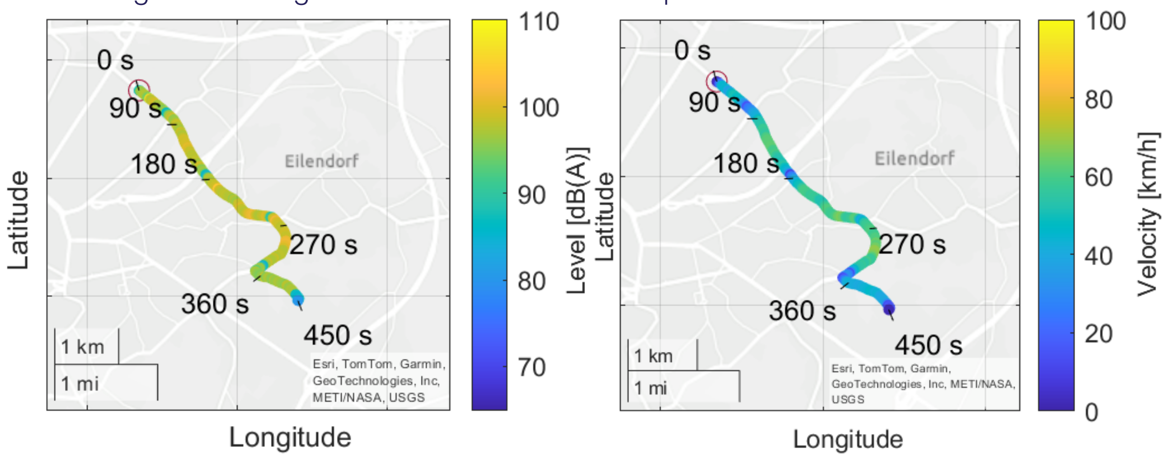

Figure 2-11: On-road resuts with on-board sensor (left: level vs. drive, right: velocity vs. drive).

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Finding 2: Engine speed, load, and vehicle velocity are the dominant determinants of noise emissions in real-world operation.

- Across the entire dataset, engine operating parameters showed the strongest correlation with measured noise levels. High engine speed and high load consistently generated notable increases in sound pressure level, both in the on-board measurements and during replicated track tests. For real-world on-board measurements, these results are shown in Figure 2-11. For the driving patterns conducted at an acoustic test track, the results of all vehicles driving a constant speed with high rpm can be found in Figure 2-12. The effect was especially evident during conditions involving aggressive throttle application and acceleration, where rapid changes in engine state produced abrupt acoustic peaks.
- Although higher-performance vehicles generally produced higher noise levels, this relationship was not uniform. Some smaller and less powerful vehicles generated similar or even higher peaks when operated under high-load or transient conditions. This suggests that real-world acoustic behavior is the result of complex interactions between engine characteristics, drivetrain configuration, and rider input.
- The analysis confirmed that the current TA methodology does not sufficiently represent the operating ranges in which real-world noise maxima occur. Emissions measured under moderate, steady-state TA conditions fail to reflect the dynamic interplay of speed, load, and acceleration that dominates in genuine traffic environments.

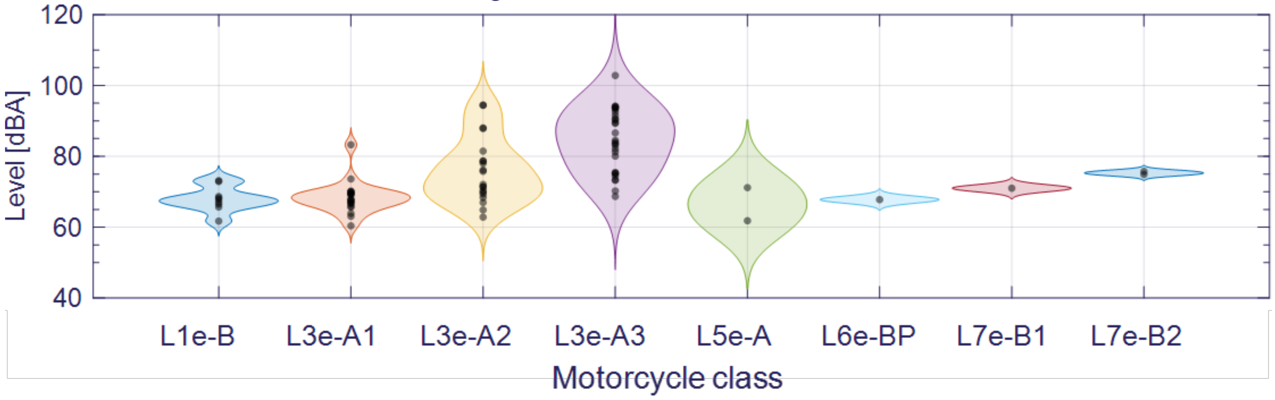

Figure 2-12: Results from real world driving pattern conducted at acoustic test track, pattern 10 [high rpm at constant speed].

Finding 3: On-board noise measurement is feasible and robust, but its implementation presents technical and methodological challenges.

- The on-board system developed in the project reached TRL 7 and successfully operated on 14 vehicles. It continuously recorded synchronized acoustic, positional, and dynamic data. The system proved suitable for capturing long-duration, real-world noise behavior and for deriving representative driving patterns.
- Several challenges emerged during deployment. Background interference from wind, surrounding traffic, or vehicle-internal sources occasionally complicated the interpretation of acoustic data, requiring careful processing and filtering. Mounting constraints and variability in vehicle geometries introduced additional complexity, particularly for the consistent placement of sensors and the mitigation of mechanical coupling effects.

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- The methodology enabled the identification of noise-relevant driving events and provided a consistent basis for linking on-road measurements with controlled test-track replications. This integration of technical measurements with subjective assessments from listening studies created a comprehensive framework for evaluating noise annoyance and identifying the most critical contributors under real operating conditions.

In summary, a methodological link between controlled laboratory and type approval testing and the complex, variable acoustic behavior observed in real traffic has been developed. By systematically comparing both domains, it identifies the key sources of discrepancy and provides concrete technical recommendations for refining TA procedures. The outcomes form the scientific basis for future revisions of L-category noise legislation, ensuring that upcoming standards reflect the true acoustic performance of vehicles in everyday use.

2.3.2 Suggested revisions to TA procedure for noise emission

Based on the findings, of which the most relevant ones have been outlined above, the following recommendations can be derived:

Recommendation 1: Harmonize Type Approval Procedures Across L-Category Regulations
The analysis from deliverable 4.5 [5] revealed substantial procedural differences between the applicable UN regulations. Standardizing elements such as test mass definitions, test types, measurement zone lengths, and gear-selection logic would enhance comparability across vehicle categories and reduce ambiguity within the type-approval process.

Recommendation 2: Reevaluate the (RD-) ASEP Boundary Conditions, Especially Engine Speed Limits
Current (RD)-ASEP requirements exclude many real-world high-noise scenarios, particularly those involving high engine load at low vehicle speeds. Adjusting the control ranges – especially the upper engine-speed threshold – would enable these conditions to be properly captured and regulated.

Recommendation 3: Integrate Real-World High-Noise Maneuvers into Regulatory Procedures
Frequent and noise-intensive driving behaviors, such as aggressive acceleration or sudden throttle bursts, are not adequately represented in current test protocols. These maneuvers should be formally defined and incorporated into type-approval routines to ensure realistic and representative acoustic assessments.

Recommendation 4: Harmonize Noise Testing Across Vehicle Subtypes and Drive Technologies
The application of ASEP and RD-ASEP provisions is currently inconsistent across LV subcategories and drive concepts. A unified regulatory framework is needed to ensure that hybrid systems, CVTs, and other modern technologies are assessed fairly and comprehensively.

Recommendation 5: Allow Flexible but Reproducible Testing Conditions Reflecting Urban Environments
ISO-standard test tracks provide controlled environments but do not capture the acoustic complexity

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of urban areas. Supplementary, well-defined urban test procedures—supported by portable measurement systems—should therefore be permitted to increase real-world relevance while maintaining reproducibility. This recommendation is not limited to LVs but all vehicles contributing to traffic noise.

Noise emissions from L-category vehicles remain a persistent challenge in urban soundscapes. The data collected within the LENS project shows a mismatch between what is tested in regulation and what occurs on the road. This mismatch is dependent on the LV subcategory and the respective regulation. The recommendations presented in deliverable 4.5 [5] and stated here aim to bridge this gap by promoting regulatory modernization that is technically robust and practically implementable. They balance scientific accuracy, regulatory harmonization, and enforceability. Adopting these proposals would represent a significant step toward a more effective noise-control strategy across Europe for powered two- and three-wheelers as well as quadricycles. This deliverable provides a critical evaluation of current procedures and outlines potential improvements to enhance the accuracy, relevance, and representativeness of noise measurements. Ultimately, the goal is to support the development of more robust and effective noise type-approval procedures that reflect real-world vehicle use and evolve regulatory expectations.

2.4. Detection techniques for tampered L-category vehicles

The objectives of this work package were to:

- Review methods for tampering of LVs and their impact on noise and pollutant emissions [7]
- Further develop, adapt, and validate roadside measurement techniques to detect tampered LVs
- Deploy roadside detection techniques in field surveys to screen for tampered LVs
- Link the results from screening surveys to roadside inspections of suspected tampered LVs
- Synthesize the survey results to propose mitigation actions to prevent tampering of LVs [8]

2.4.1 L-vehicles tampering & undesirable effects

Tampering practices in L-category vehicles (motorcycles, mopeds, tricycles, quadricycles) have been investigated across the European Union and assessing their environmental impacts [7]. The study aimed to identify the most common tampering methods currently applied and to qualitatively evaluate their effects on pollutant emissions and noise.

The assessment combines four data sources: a structured literature review, partners' own previous knowledge, an online questionnaire completed by 602 respondents, and 64 face-to-face interviews in Greece. The questionnaire targeted owners of L-vehicles who had implemented at least one modification. Questions covered vehicle characteristics, types of tampering, motivations, implementation details, and usage patterns. The analysis also explored demographic factors, vehicle categories, and annual mileage to estimate the relative contribution of each modification to overall emissions impacts.

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Tampering methods were categorized to affect exhaust, air intake, fuel system, ECU/electronics, engine, transmission, and fairing. A qualitative effects table was compiled summarizing whether each modification increases, decreases, or does not affect CO, CO_2, NOx, HC, and noise levels.

Tampering is widespread across the EU and heavily skewed toward performance-oriented motorcycle owners:

- Most respondents were male and between 20–50 years old.
- Most owners of tampered vehicles use the vehicle mainly during free time, not commuting.
- 2/3 of respondents owned used vehicles, suggesting higher tampering likelihood in second hand LVs.

Most owners made only 1–2 modifications, but a significant group (19%) applied more than six, indicating a highly tuned subset of vehicles. Comparisons between online and in-person Greek surveys showed strong consistency, validating the online dataset.

The modifications identified are listed in Figure 2-13, which also shows which were the most frequent ones.

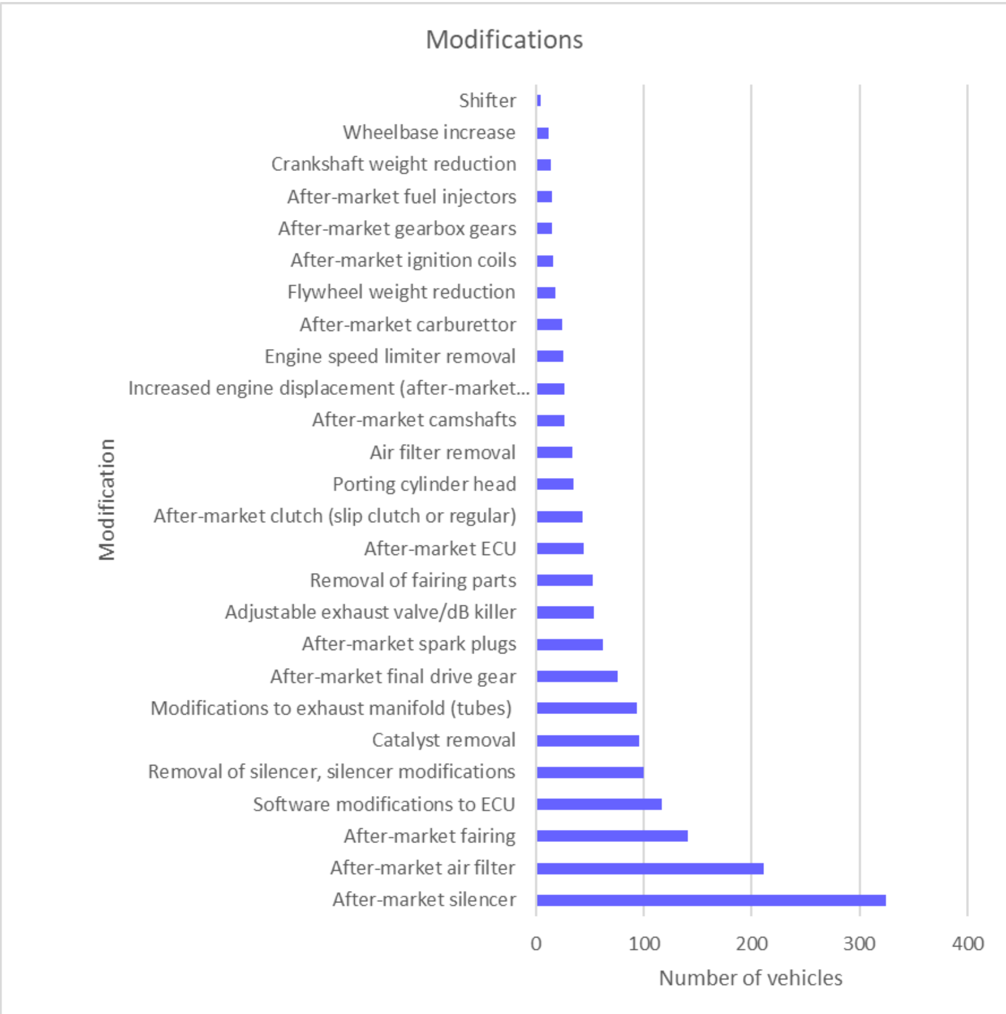

Figure 2-13: Number of vehicles that have implemented each modification. Data from the online questionnaires and in-person interviews.

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The most tampered systems were: exhaust (36%), ECU/electronics (16%), and air intake (14%). Across all categories, the primary motivation for the modifications by the respondents was increased engine power (47%). Secondary motivations included "better" sound (21%), better appearance (13%), better handling (8%) and fuel economy improvements (11%).

Except for identifying the most common tampering techniques, a qualitative approach was used for the documentation of the effects that these modifications may have on pollutants (CO, NOx, HC), carbon dioxide (CO2), and noise emission levels. The Qualitative documentation of the effects provided essential guidelines for the identification of tampering during the subsequent LENS experimental campaigns (RDE and remote sensing).

Deliverable D5.1 [7] demonstrated that L-vehicle tampering is widespread, diverse, and often leads to increased pollutant & noise emissions The most common and impactful modifications involve the exhaust system, air intake, and ECU/electronics. Catalyst removal and ECU reprogramming are among the most harmful practices for pollutant emissions, while silencer changes and dB-killer removal contribute extensively to excessive noise in urban environments.

2.4.2 Techniques for tampered and high emitting LV detection

In preparation of the in-field surveys (D5.3) [8], instruments and methods were developed for roadside measurements of LV noise and pollutant emissions. To thoroughly and refine all measurement approaches and their interoperability prior to the LENS in-field surveys, the noise and point sampling measurement systems have been deployed together during a validation measurement campaign in Graz (Austria), where various types of LVs were driven past the instruments covering a broad range of common driving condition.

The devices used for point sampling have been referenced either in the lab or at the test-bench at TU Graz. The calibration campaign of the black carbon measurement instruments has shown that the behavior of the used BC-tracker is reliable over a wide concentration range and unessentially influenced by the soot composition, in comparison to an aethalometer. The used reference device was calibrated by gravimetric filter weighting beforehand. The test bench measurements compared the PEMS measurements with the lab analyzers of the test bench and an Engine Exhaust Particle Sizer (EEPS), which is also used for the point sampling efforts. The results show a very good correlation for all measurements.

The experiments with optical gas imaging by Schlieren Imaging have been successful to verify the principle of operation. The goal is to develop a setup which allows to visualize the spread of the plume and apply it at one in-field measurement campaign.

The analyses have shown that the point sampling technique for roadside pollutant emission measurements is very likely not feasible to detect tampered LVs reliably – cf. Figure 2-14. The correlation between point sampling measurements of LVs equipped with PEMS was very poor and analysis of the time series shows that, by point sampling, a pass by can hardly be detected. This is due to the comparably low exhaust mass flow from the small LV engines. Although the pollutant concentration in the undiluted exhaust is high (according to data from WPs 3 and 4), the total emitted amount is very low, so that single passing vehicles do not cause concentration events which are detectable from the roadside.

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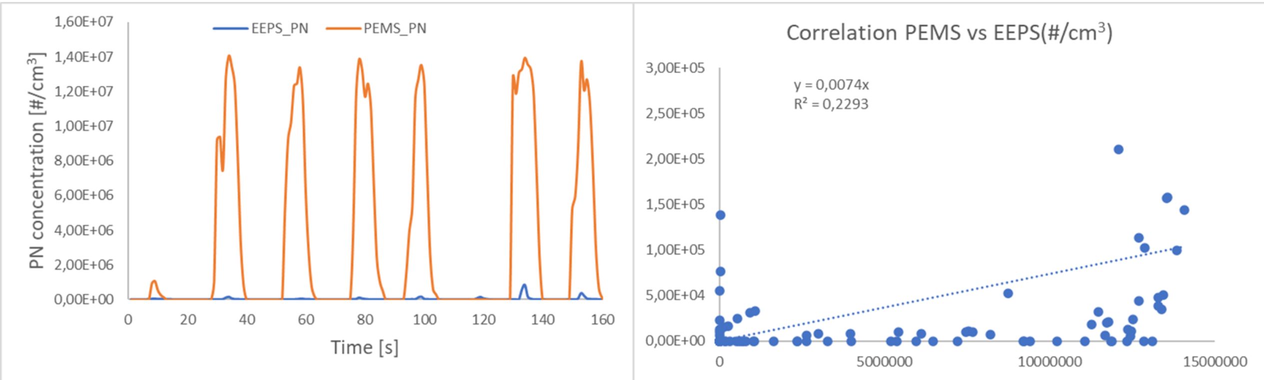

Figure 2-14: Results for the comparison of the particle number (PN) measurements by means of the roadside point sampling technique and onboard with PEMS. Time series (left) and correlation plot (right).

The noise measurement system consists of a linear array of five microphones, a data acquisition system and a laptop for data storage and processing. Sound measurements automatically start and stop based on continuous monitoring of the instantaneous sound pressure level. The recorded signals are further analyzed in terms of sound pressure levels, but also other metrics characterizing specific aspects of the sound signature and holding potential as tampering indicators. Because no dataset with labeled recordings of both tampered and not-tampered LVs measured in a consistent way was available before the in-field surveys, only a preliminary analysis of possible sound features for detecting tampering has been carried out using a variety of available datasets with either unlabeled recordings or recordings of only not tampered LVs.

2.4.3 Results of field surveys on LV tampering

Measurements of pollutant emissions and noise by roadside instruments were carried out on individual passing LVs in three EU cities/regions:

- Leuven
- Paris region (Rueil Malmaison and Dampierre-en-Yvelines)
- Barcelona

The measurements were combined with roadside inspections (visual inspections, idle CO and HC emissions tests and stationary noise tests on a subset of L-vehicles being pulled over by the local police). In all, the pollutant (CO, HC, NO, NO_2 – i.e., NO_X – NH_3 and PM) emissions of more than 2,000 LVs were measured, of which about 260 LVs went through a roadside inspection.

Regarding pollutant emissions, the following findings and conclusions were made:

- On-road emissions of all regulated pollutants CO, HC and NO_X have been reduced substantially from early Euro classes to Euro 5, with reductions in the range of ≈60 – 90%, depending on pollutant. For particle mass and number, reductions were even larger.
- Compared to cars, the hit rates for measuring emissions from passing L-vehicles from the roadside are low or even very low, making such measurements mode demanding and less effective for detecting the condition of vehicles on the road.
- Emission modifications/tampering increase the on-road emissions of CO, HC and PM by a factor of 5-10, whereas NO_X emissions tend not to be impacted – cf. Figure 2-15 (top).

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- According to the roadside inspections, the share of tampered LVs was slightly above 10%, including both emission and noise tampering. Since not all tampering options were included in the inspections – for example it was not possible to detect whether <50 cc LVs had their speed limited disconnected or removed – this tampering share should be expected to represent a minimum.

Regarding noise, the following findings and conclusions were made:

- The distributions of the sound pressure level (LAFmax) measured at the roadside were comparable for all measurement sites, with similar median levels and many outliers to much higher levels that are mostly due to specific driving conditions (e.g., revving).
- The in-field observations do not reflect the gradual improvements in the type approval regulations for LV noise. However, these observations are strongly influenced by - among others - the composition of the measured fleet, the vehicle condition and especially the driving conditions, which where far from the most noise critical for most LVs.
- Compared to the inspected vehicles where no signs of tampering were observed, most tampered vehicles exhibit higher levels in the stationary noise test but not necessarily in the noise levels measured from the roadside. The choice of the weighting filter has a big impact on the observed difference in sound pressure level for noise tampered vehicles – cf. Figure 2-15 (bottom).
- A large number of signal features, including psychoacoustic metrics, signal statistics and various features designed for machinery condition monitoring, have been analysed and mostly showed consistent results for the complete fleet all measurement sites. Comparing tampered vehicles and inspected vehicles for which no signs of tampering were observed, significant differences can be observed for certain metrics (e.g. roughness).
- Due to the limited number of recordings corresponding to tampered LVs, it was not possible to train a robust and versatile tampering detection model. However, preliminary results show that – with more training data – it could be possible to derive a model to detect certain types of tampering based on the LV sound signature.

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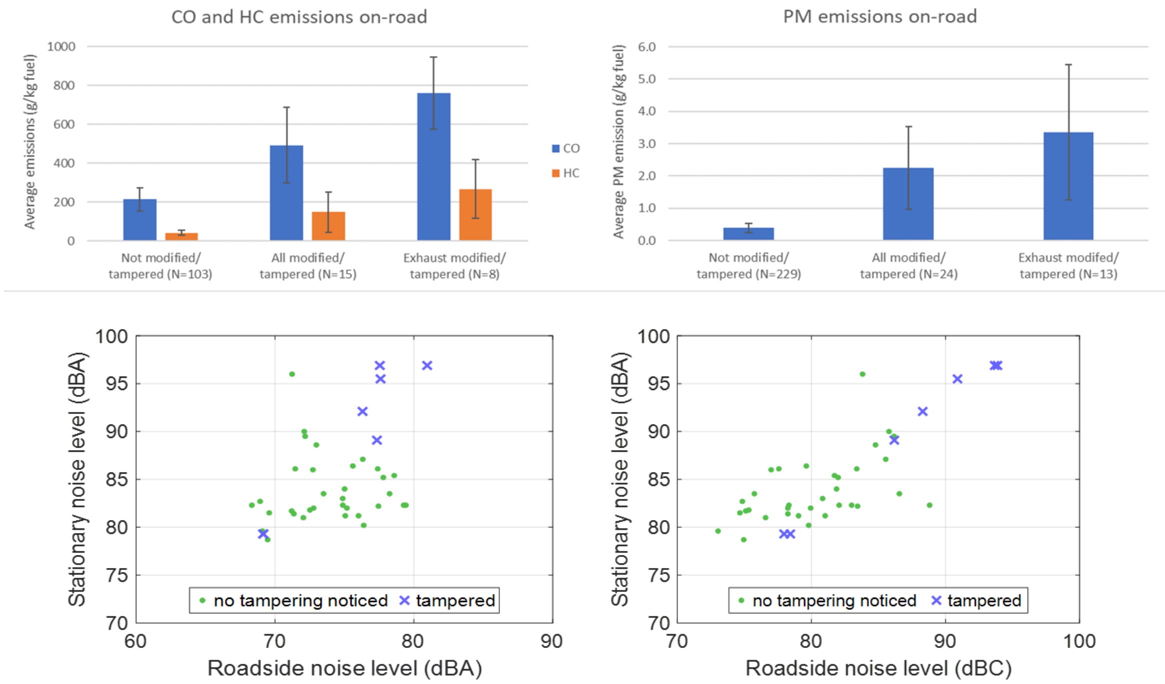

Figure 2-15: *Top:* Impact of modification/tampering on CO, HC and PM (particle mass) on-road emissions (in g/kg fuel) for the LVs inspected at the roadside inspections in Leuven and Barcelona. *Bottom:* Relation between stationary noise level (dB(A)) and roadside noise level, expressed as maximum A-weighted (L_{AFmax}) and C-weighted (L_{CFmax}) sound pressure level.

2.5. Assessment & intervention options

In order to be able to propose and define policy recommendations, many steps are required. The first is to review real world operation patterns and limitations on the requirements and set-up on new procedure for testing to improve L-category vehicles real world behavior in a near future. Another step is also to assess emission and noise contributions in real driving conditions at a local and global (EU) scale. Then demonstrate impacts of interventions by scenario simulations and make technical and policy recommendations on how fleet and new L-category vehicles can become cleaner and quieter [8]. On top of that one of the approaches hosted by this section is the enhancement of a (free) mobility app on best practices guidance for riders.

2.5.1 Case-studies & intervention options

As the real driving conditions have been studied, an investigation can be made on the scenarios that could have an impact on the pollutant and noise emissions of L-category vehicles and on the tools modelling tools that will help to assess these impacts as the ultimate goal of the LENS project is to provide policy recommendations for cleaner and quieter L-category vehicles.

The main types of intervention envisaged to reduce emissions and noise from L-category vehicles are as follows:

- Changes in certification standards: These include the introduction of more stringent emissions and noise standards, covering tailpipe emissions testing, the introduction of a PN limit, the

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potential implementation of off-cycle emissions testing, and on the standard method for roadside enforcement testing for noise. These scenarios will be translated into assumptions about the corresponding technological developments, from the most conservative to incremental technical advances and potential new breakthroughs.

- Anti-tampering measures: Many different measures can be envisaged to combat the proliferation of manipulation of L-category vehicles. These may include measures aimed at strengthening roadside checks (by making them more effective, increasing their number, increasing fines, etc.). It may involve making these modifications more difficult to carry out (banning non-certified and easily modifiable parts, prohibiting the sale of noise-increasing parts, etc.).
- Local regulations and driver behaviour: Several local regulations can be considered to reduce the contribution of L-category vehicles to emissions and noise in designated areas, for example: closing roads or restricting access to L-category vehicles in designated areas, introducing specific speed limits in sensitive areas, setting up low-emission zones, quiet zones and protected quiet zones, incorporating innovative road and infrastructure planning measures, enforcing maximum noise limits on building facades or along roads, and implementing automatic enforcement. These measures aim to influence both the composition of the local fleet and driver behaviour. Additional measures can be deployed to influence such behaviour: implementation of strict penalties, enforcement of vehicle roadside inspection, use of information and warning signs strategically placed along roads, and increased fines.

The LENS project uses various modelling tools to assess emissions and noise from L-category vehicles.
To assess pollutant emissions, LENS uses the PHEM, MobSim and COPERT models:

- PHEM (Passenger car and Heavy-duty Emission model) is an instantaneous emission model based on longitudinal vehicle dynamics equations and engine emission maps. PHEM will be used to generate emission factors for various representative driving cycles, road gradients and driving styles. LENS test data will be used to parameterize PHEM.
- MobSim is another microscopic pollutant emission model developed by IFPEN. Like PHEM, it uses real-life data to simulate emissions under various driving conditions. The results of PHEM and MobSim will be compared, and synergies sought.
- COPERT [15]is the EU's standard vehicle emissions calculator. It uses vehicle population, mileage, speed, and environmental factors to calculate emissions. COPERT includes emission factors for over 450 vehicle types, including L-category vehicles. The LENS data will be used to update the emission factors for L-category vehicles in COPERT.

To assess noise, LENS mainly uses ROTRANOMO [16], a microscopic road traffic noise model that calculates the noise levels of individual vehicles as a function of their speed and acceleration. It considers propulsion noise and rolling noise separately. ROTRANOMO uses a detailed classification of vehicle categories, including sub-categories for L-category vehicles. Noise measurements made as part of the LENS project will be used to update the ROTRANOMO model.

In addition to PHEM, MobSim, COPERT and ROTRANOMO, LENS also uses the SIBYL [17] and TRANECAM tools to model large-scale and national impacts:

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- SIBYL is a modelling tool used to forecast the effects of changing vehicle technology on future vehicle fleets, energy consumption and emissions. It is used to assess the impact of different policy options on road transport emissions.
- TRANECAM is a model that calculates the 24-hour average noise level for different road types and traffic situations. It is used to assess the impact of noise limit modifications and other mitigation measures on noise exposure.

Table 2-2 Overview of models and outputs for foreseen analysis of noise and emissions at local and global level in LENS

	Model/approach	Local	Global	Outputs
Pollutant emissions	PHEM	X	X	1hz emissions [mg/s] on generic real-driving use cases, dataset of emission factors [mg/km] to feed COPERT
	MobSim & RTAMS	X		Emissions [g/h] of the fleet on each road segment of a dedicated local area
	COPERT		X	Emission factors per vehicle category [mg/km] & Total emissions [tonnes] at state level
	SYBYL		X	Total emissions [tonnes], benefits, and implementation costs of mitigation solutions (CBA)
Noise emissions	Rotranomo	X		Second by second noise emission for driving cycles
	Tranecam	X	X	Emission factors per vehicle category, emission stage and traffic situation, L_{den} and L_{eq}
	CNOSSOS	X	X	Emission factor per vehicle category (for L_{den})
	Phenomena/MN/Lcat		X	L_{den} + CBA
	Single events	X	X	Delta L_{Amax} average

LENS will use a platform called R-TAMS to assess the local impact of L-category vehicles. R-TAMS is a modelling platform that estimates pollutant emissions and road traffic noise for each road section in a study area. It considers traffic volumes, vehicle fleets and emission factors. R-TAMS will be used to assess the impact of mitigation measures in the three cities selected for the WP5 pilot experiments.

CBA is foreseen for mitigation measures at global level, for those scenarios with substantial impact. Approaches used in previous studies such as EU sound limits studies [12], [13] and the Phenomena study [18] can be adopted where required, for example noise scenarios and single event analysis.

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In order to carry out the evaluations required for the LENS project, several developments are necessary and on-going:

- Integration of LENS data into existing modelling tools: Emissions and noise data collected during the LENS project's RDE road and laboratory tests will be used to update the PHEM, COPERT and ROTRANOMO/TRANECAM modelling tools.
- Development of emission factors for L-category vehicles: the LENS project will use the PHEM model to create a set of representative emission factors for the distinct categories of L-category vehicles. These emission factors will be used to evaluate both reference and intervention scenarios.
- Development of noise emission factors for L-vehicles suitable for use in the EU noise mapping model CNOSSOS-EU.
- Consideration of eco-driving: An eco-driving model from the H2020 uCARe project will be adapted to L-vehicles to analyse the effects of modified driving behaviour on emissions.
- Development of local intervention scenarios: In addition to national and European assessments, local intervention scenarios will be developed for the three LENS pilot sites. These scenarios will take account of local specificities, such as the composition of the vehicle fleet and traffic flows.
- Assessing the impact of regulatory changes: The models will be used to assess the impact of regulatory changes, such as the adoption of stricter Euro V+ standards or the implementation of anti-tampering measures.

Using this combination of modelling tools and new developments, LENS aims to provide a comprehensive assessment of the impact of L-category vehicles on air and noise pollution. The results of these assessments will be used to develop public policy recommendations aimed at reducing this impact.

2.5.2 Eco-mobility app for best practices on LV use

Through all the work packages and deliverables of the LENS project, a lot of knowledge has been gained toward the real world behavior and usage of L-category vehicles. These knowledges have been integrated into the Geco air app [20], which is a mobility companion developed by IFP Energies Nouvelles (IFPEN) to encourage sustainable mobility practices and reduce environmental impacts. This app is available on the iOS and Android stores for free, to offer its access and use to as many people as possible. The app is engineered to analyze travel habits and assess the environmental impact of individual trips across various transport modes. By assigning users a “mobility score” it provides tailored recommendations to help them reduce their CO_2 and pollutant emissions, see Figure 2-16.

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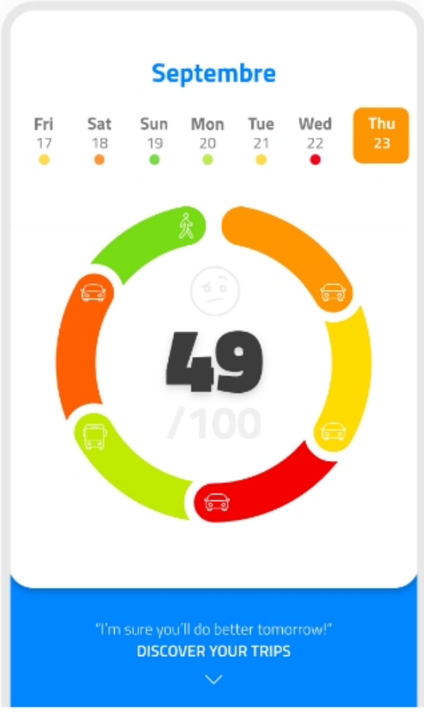

Figure 2-16: Example of mobility score delivered by the Geco air application showing the contribution all over the day with multiple transportation modes with various footprints.

The app's user-friendly interface offers actionable advice, such as driving behavior adjustments and alternative travel options, enabling users to make informed decisions that align with eco-friendly practices. A key feature of the app is its ability to simulate eco-driving behaviors through advanced virtual driver models, which guide users in adopting smoother and more energy-efficient driving techniques. This makes the Geco air app a practical and accessible tool for individuals seeking to minimize their environmental footprint. The LENS project has played a pivotal role in enhancing the Geco air app by addressing significant data gaps related to L-category vehicles, such as motorcycles, mopeds, and scooters. These vehicles contribute substantially to urban traffic but have been underrepresented in emissions studies. To address this, the project developed a detailed database of more than 150 L-category vehicles tested under both type-approval and real-world conditions thanks to the work performed under WP3 and WP4. This data was instrumental in refining the app's emissions and fuel consumption models, ensuring that the recommendations it generates are accurate, reliable, and reflective of actual driving conditions. The app's recent updates include personalized tips to mitigate harsh driving behaviors, reviewed in WP5 and WP6 through the D6.1 for example, such as rapid acceleration or braking, which are known to increase fuel consumption and emissions significantly, see Figure 2-17. Despite certain limitations, like the challenge of relying on GPS data for precise emissions calculations, the app has proven its ability to provide reliable estimates and encourage positive behavioral changes. Its intuitive design and advanced features make it an effective tool for promoting sustainable transportation habits among users.

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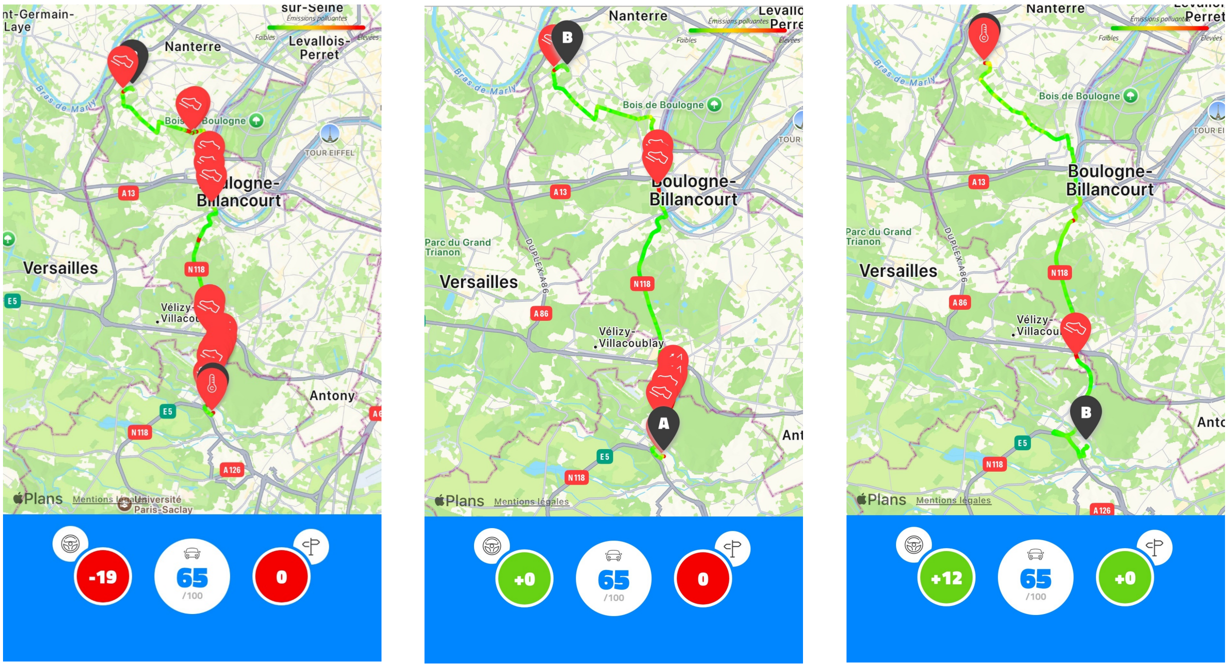

Figure 2-17: Example of outputs from Geco air on the driving behavior for three similar trips with different driving behavior for the same driver using the same motorbike.

Furthermore, the dissemination efforts driven by the LENS project have expanded the Geco air app's reach across Europe, showcasing its potential as a leading solution for eco-friendly mobility. The work performed under the LENS project underlines the need for broader implications of integrating such digital tools into transportation ecosystems. By leveraging real-world data, advanced analytics, and personalized feedback, the Geco air app not only enhances the understanding of L-category vehicle emissions but also empowers individuals to make more sustainable choices. This initiative aligns with global efforts to combat climate change, reduce urban air pollution, and improve the overall quality of life in cities.

The impact of interventions to reduce noise and emissions of L-vehicles was assessed in a scenario analysis and cost-benefit analysis, including:

- Improved vehicle type approval regulations.
- Reduced vehicle tampering and modifications.
- Local regulations and enforcement of driving behaviour.
- Access restrictions.
- Accelerated fleet renewal.

Also, driver communication and awareness and improved environmental regulations were considered in a qualitative manner.

All the scenarios mostly for noise have a positive benefit to cost ratio for the period 2025-2050, although some are more costly to implement than others, in particular vehicle replacement incentives involving state subsidies. Some interventions such as improved type approval regulations only affect the new fleet and not existing vehicles and therefore take many years to reach full impact. Others such

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as enforcement of driving behavior and access restrictions can take effect immediately when implemented, affecting the whole fleet. Reduction for vehicle tampering is most cost effective and requires widespread implementation by increased roadside and periodic technical inspections. The current environmental instruments to address high sound emitters are insufficient and could be better addressed in the END, for example by sound penalties and higher does-effect relationships for L-vehicles.

Regarding emissions, scenarios related to type approval regulations and fleet renewal both resulted in a positive benefit to cost ratio (above 1) for the period 2025-2050. The regulatory measures were assessed through two sub-scenarios, namely introduction of RDE limits and implementation of stricter WMTC limits, with the former achieving the highest net benefit overall. For the scenarios targeting reduced vehicle tampering and changes in driving behavior, only a benefit analysis was conducted, since estimating total implementation costs proved highly uncertain, especially due to infrastructure and indirect societal costs. However, their monetized benefits can be integrated with the corresponding noise-related benefits, in order to succeed in higher benefits. Finally, the fleet renewal scenario results in substantially higher costs than the type-approval scenarios, chiefly because it relies on state subsidies. Nevertheless, especially in this scenario, the emission benefits from fleet renewal can also be combined with the monetized noise benefits, since fleet renewal typically replaces older vehicles with newer, quitter models that simultaneously reduce both noise and emissions.

All of the considered interventions can be implemented by specific policies and stakeholders, which is discussed in the following chapter.

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3 Mitigation options and policy recommendations

The LENS project has provided extensive evidence that current noise emission regulations for L-category vehicles require significant revision to adequately address real-world noise pollution. Comprehensive measurement campaigns reveal a complex landscape where vehicle performance characteristics, driver behavior, and specific operating conditions interact to produce noise emissions that often exceed what standard type approval testing captures.

The extensive exhaust emission testing campaign conducted with over 150 vehicles in the lab or on-road revealed that current exhaust emission regulations do not satisfactorily cover real-world operation. Vehicles that meet Euro 5 limits under WMTC frequently emit substantially higher CO, HC and NOx during real-driving conditions. This is especially relevant during more dynamic/sportive operating points, such as acceleration from stand-still, deceleration transitions, merging and overtaking maneuvers on highways or rural roads. Elevated levels of non-regulated pollutants (PN, NH_3) were also observed, highlighting the need for addressing these species in type approval.

L-vehicles have some of the highest sound levels compared to other vehicles, in particular those that are high powered and the modified/tampered ones. The sound levels strongly depend on engine speed and load, so high acceleration, engine revving and acceleration from standstill can produce high sound levels. Therefore, mitigation measures affecting driving behavior and vehicle condition (tampering, maintenance, etc.) play a significant role as their impact is not affecting only the new vehicles in the fleet, but also the existing vehicles.

Type approval regulations for noise set the allowed noise emission of new vehicles under average conditions but insufficiently cover all loud driving conditions. In particular older vehicles do not comply with more recent versions of the regulations, and more so if they are tampered. Another aspect for L-vehicles is that they are not sufficiently regulated in terms of environmental noise regulations, which are based on long term average traffic sound levels. Due to the characteristics of sound fluctuation, impulsiveness, tonality and frequency content, besides the actual sound level, they have a high annoyance score in public noise surveys.

The main options for noise and emissions mitigation, the involved stakeholders, impact and obstacles are described in the following. All the proposed instruments are deemed to have a positive benefit-to cost ratio and positive health and amenity impact on citizens.

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3.1. Improvement of type approval regulations

Noise testing: Type-approval sound testing needs to cover additional operation conditions, primarily including speeds above 100 km/h and accelerations from 50 km/h on.

The UN type approval regulations for L-vehicles have room for improvement to cover the full potential range of loud driving conditions, including acceleration from standstill, acceleration from above 50 km/h to higher speeds, engine revving and others. High sound levels above 90 dB(A) are still allowed for high engine speeds, and speeds above 100 km/h and very low speeds are not covered. Also, the sound limits for the wide-open throttle acceleration should be lowered by 2-5 dB. Once introduced, this will affect all new vehicles, and throughout the EU, but not the existing fleet.

On-road emissions testing: Testing on the road – similar to RDE for passenger cars - is more technically demanding for L-Vehicles due to small size of some vehicles to carry the measurement instrumentation, accurate determination of the exhaust flow, and additional resistances imposed on the vehicles. Still, LENS consortium clearly suggests to further explore this possibility, which should allow much better coverage of real-world vehicle emission control. Such an approach should include boundary conditions tailored to each sub-category vehicle, consider equipment-weight effects, and apply appropriate driving-dynamic constraints based on L-category characteristics.

In-lab chassis testing: Several aspects of in lab emissions testing must be revised to offer better emission control:

- Re-examine road-load and running-resistance settings using improved coast-down methods, incorporating aerodynamic factors, and aligning procedures more closely with passenger-car regulation approaches.
- Allow free gear shifting.
- Increase maximum speed and maximum acceleration from stand-still in the test cycle, and integrate high load and high engine speed operation.
- Revisit the phase-weighting for the different vehicle types.
- Redefine vehicle classes using the power-to-mass ratio (PMR).

New pollutants: The inclusion of additional pollutants in type approval, especially particulate number (PN) ammonia (NH_3) and, possible particulate mass (PM), is recommended since LENS identified high levels of these pollutants on average from Euro 5 L-category vehicles.

Stakeholders, impact and obstacles

The initiation of improved type approval regulations lies with the UNECE, with proposals provided by stakeholders such as OEMs, national authorities, vehicle authorities, non-governmental organizations (NGOs) and others. Depending on the amendments, the time required for introduction can be several years. The impact is only for new vehicles for which this amended legislation is valid, therefore the benefits to citizens take much longer, i.e. as long as the average vehicle life span. Potential obstacles are reaching agreement on sufficiently effective proposals and their proper implementation in practice, besides possible circumvention methods including tampering and vehicle modification.

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3.2. Reduction of vehicle tampering and modifications

L-category vehicles have unique in-use lifecycle characteristics that differ from other vehicle categories, with more local-urban use patterns and higher tendency to tampering, creating specific environmental compliance challenges. Vehicle tampering and modification are a major cause of excessive noise and emissions from L-vehicles, and include many forms, both mechanical and electronic, and are readily available as parts, tools and services on the market. Tampering incidents typically emerge years after initial vehicle certification, affecting both noise and emission characteristics.

Some forms of tampering are easily recognized or detected, such as non-compliant exhausts or removed dB killers, but others, such as ECU modifications, engine modifications (over-displacement, pistons, camshafts) or modified transmissions may not. Any vehicle modification can potentially invalidate the vehicle road permit, potentially leading to fines or temporary permit withdrawal. Noncompliance can occur when replacement parts are installed that are non-original or non-certified. Also, parts are sometimes installed that are only intended for off-road and sports use.

Tampering can be reduced in the following ways:

- Include noise tampering in vehicle inspection, at the periodic technical inspection (PTI) and at change of owner through tampering detection techniques for both emission and noise control systems
- Provision of support tools for enforcement and inspection staff, such as apps and information resources on tampering, for example image comparison for original vehicle and components, list of potential modifications and detection methods; possibly with AI support in future, standardized access to VIN (vehicle identification number) based data on the mitigation systems included in the vehicle to check its presence and operation
- Information on effects of tampering, modifications and penalties to owners, including how to restore vehicle to a compliant state
- Automated detection of tampering and modifications, such as apps for roadside and PTI inspection, or integration in noise cameras
- Stricter regulations and penalties for tampered vehicles
- Increased resources in enforcement by police and vehicle authorities
- Market surveillance and enforcement to reduce availability of tampering sets, tools and services

The landscape of Periodic Technical Inspection (PTI) for motorcycles across Europe exhibits considerable variation. European Union Directive 2014/45/EU mandates inspections exclusively for motorcycles exceeding 125cc (categories L3e, L4e, L5e, L6e, and L7e), while explicitly exempting mopeds and lightweight motorcycles (categories L1e/L2e ≤ 125cc and ≤ 11kW). Although the EU-wide directive does not require PTI for mopeds, certain Member States have instituted more stringent regulations independently. For instance, the Netherlands and Spain have broadened mandatory inspection requirements to encompass mopeds, whereas the majority of countries adhere to the minimum EU requirements, thus providing complete exemptions for these vehicles. Implementation practices vary substantially throughout the European Union. This regulatory fragmentation regarding

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small-displacement vehicles engenders inconsistency across Member States, resulting in significant deficiencies in the monitoring of environmental and safety performance for the substantial number of mopeds currently in operation throughout Europe.

CITA, the international association of public and private sector organizations actively involved in mandatory road vehicle compliance, have provided a series of practical recommendations in relation to improving in-service conformity vehicle inspection in a document provided to the LENS project [19]. Processes could be significantly facilitated and improved if inspection requirements and procedures are properly considered in advance during the Type Approval phase, enabling clearer identification criteria and more efficient assessment protocols. Component failures in emissions control and noise reduction often go undetected, whereas maintenance and repair practices significantly impact both noise and emission performance.

In-use inspection processes could be significantly facilitated and improved if inspection requirements and procedures are properly considered in advance during the type approval phase, enabling clearer identification criteria and more efficient assessment protocols. The current challenges with M-category vehicles equipped with advanced environmental control systems (Selective Catalyst Reduction, SCR; Exhaust Gas Recirculation, EGR; Particulate Filters) highlight the importance of considering in-service testing during the design phase. These systems are difficult to properly assess during Periodic Technical Inspection (PTI) because inspection accessibility and real-world performance verification were not prioritized or, sometimes, even considered during type approval. The influence of these systems over the real in-use emissions of the fleet has forced the development of in-service inspection methods and rejection limits based on reverse engineering. These methods are not ideal and may have been introduced earlier (with the consequential overall emission reduction with a coordinated Type Approval in-service testing approach. The most important points to be addressed are:

- Design for Environmental Inspectability:
  - Standardized diagnostic interfaces for real-world performance verification of both noise and emission systems.
  - Visual indicators or diagnostic capabilities that enable detection of environmental performance degradation.
  - Standardized inspection protocols and rejection thresholds for in-service emission and noise measurement.
- Comprehensive Detection Methods:
  - Adaptation of type approval tests for allowing in-service verification.
  - Development of practical noise measurement protocols for PTI environments.
  - Integration of emission measurement techniques suitable for routine inspection procedures.

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Stakeholders, impact and obstacles

In order to implement all the above points, different stakeholders are required. Firstly, at the regulatory level, PTI and roadside inspections need to be compulsory for L-vehicles and to properly include noise and emissions.

This requires improved regulations outlined in the EU Roadworthiness package. Secondly, they need to be sufficiently implemented by national authorities and roadside and vehicle enforcement agencies, with strong focus on the high emitters of noise and emissions. The impact of increased PTI and roadside inspections is deemed to be significant and short- term if properly focused on the multiple types of tampering, which are freely available and often simple to implement. Most citizens are well aware of the high sound levels caused by tampered vehicles, which lead to high complaint levels and for some are unbearable. There are several obstacles including

- Ease of availability and installation of tampering devices and methods.
- Rider enthusiasm for increasing power, speed and noise.
- Availability of switchable devices such as exhaust flaps, remote controlled ECUs and speed restriction devices and other less visible methods, which reduce detectability for enforcement staff.
- Lack of resources for enforcement staff.
- Lack of tools to simplify and speed up vehicle inspections such as recognition apps, databases and automated enforcement systems.
- In some countries, lack of legal instruments to properly enforce tampered vehicles, such as proportional fines and permit withdrawal.

3.3. Local regulations to control driving behavior

Driving behavior can also cause high emission and noise levels, affected by engine speed and load, for given vehicle design, condition and tampering. Driving behavior is generally controlled locally, firstly by the driver, who in turn is influenced by traffic measures such as

- Speed limits, for less acceleration and lower engine speed.
- Infrastructure changes (e.g. humps, road surface, warning signs).
- Attended enforcement of driving behaviour, for speeding, aggressive driving, revving, high rpm etc.
- Automated enforcement, such as mobile or fixed noise cameras, which need situation dependent sound limits.
- Static or dynamic warning displays related to noise.
- Information resources and training to increase driver awareness on:
  - The impacts of high sound emission and how to control it.
  - The impacts of exhaust pollutants and how dynamic and aggressive driving is correlated with increased pollutants emission.
- Citizen monitoring and feedback and signalling by wardens.

Stakeholders, impact and obstacles

Improvement of driving behavior is firstly determined by riders themselves, which is in turn influenced by many factors mentioned above, which are responsibility of police enforcement, road authorities,

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municipalities and national regulators. Also, OEMs, vehicle dealers and parts suppliers and rider associations have a role to play in communication on driving behavior and its effects. Besides this, public perception and driver awareness of the acceptability of high noise levels also play a role. Feedback from affected citizens is important to identify areas with high noise levels where action plans may be appropriate.

Based on the simulations LENS performed, improved driving behavior is expected to reduce the L-vehicle fleet pollutant emissions by 7-10%, which is substantial. Regarding noise emissions, the impact is considered significant as high noise levels can occur under certain driving conditions even within the Additional Sound Emission Provisions (ASEP) constraints. A 10 dB higher noise level exposes a tenfold higher number of people. So the reversie is true for noise reduction. A secondary impact of improved driving behavior is road safety due to lower speeds, better vehicle control and less sudden movements.

Obstacles to implementation are driver attitudes and awareness, and road situations where drivers feel the need to accelerate or speed with high noise levels.

3.4. Local access restrictions

Access restrictions are one of the instruments to reduce noise exposure for nearby residents at local level, being very effective where applied. These include partial or total entry restrictions for certain vehicle categories, times or roads. They also include:

- Low emission zones (exists for emissions but not for noise).
- Pedestrian zones and traffic restricted areas.
- Individual driving bans.

Access restrictions through low emission zones can effectively limit pollutant exposure in sensitive areas. However, as previous studies have shown, such access restrictions do not significantly reduce the whole vehicle activity, they rather shift the vehicle activity from urban environments to rural areas, or to areas outside the restricted area. While the benefits from the reduced pollutant exposure in the (most probably) densely populated restricted areas are clear and significant, overall pollutant exposure might not change substantially. In depth air quality studies need to be conducted in order to assess the impact of low emission zones.

Stakeholders, impact and obstacles

Access restrictions are typically controlled by local authorities, within the scope of general traffic regulations, and enforced by those and by the police. They can be triggered based on public complaints or considerations such as road safety and environmental impact. They can have a significant benefit for local residents at local level if resulting in less loud vehicles.

Obstacles are typically reduced access leading to alternative routing and shifting the problem elsewhere. Also, quieter vehicles may be unnecessarily restricted. In some cases, legal challenges or lack of suitable legislation may be an obstacle to implementation.

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3.5. Accelerated vehicle fleet replacement

Accelerated replacement of old vehicles by new combustion or electric vehicles over time would gradually lead to a quieter and cleaner fleet. It requires costly subsidy programs and can be linked to low emission zones for noise, allowing access only to electric vehicles for example.

Stakeholders, impact and obstacles

This type of incentive, especially electrification, is generally supported by national authorities. Over many years, the benefits may be significant once a large part of the fleet, and especially the noisier and tampered vehicles are replaced. Key obstacles to this are the costs of subsidies and the will of vehicle owners to part with older and louder vehicles.

Improvement of environmental legislation

In order to better take into account the high annoyance levels and health impacts due to L-vehicles, the Environmental Noise Directive could be updated in relation to:

- Sound emission factors for motorcycles and mopeds.
- Penalty or separate dose-effect relationship for L-vehicles.
- Including L-vehicles in the counting for traffic flow.

Stakeholders, impact and obstacles

This initiative would need to be proposed by EU member states and the European Commission. Its impact would be to better quantify the effects of loud L-vehicles on annoyance, sleep disturbance and health, and to trigger specific action plans for loud vehicles such as extra enforcement, noise cameras and driver warning systems. Potential obstacles are the will of member states to undertake this and practical issues such as counting of L-vehicles and the assessment of tampering rates and driving behavior.

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4 Follow-up and Future work

Based on the findings and results of the LENS project, Table 4-1 outlines key follow-up actions recommended by the LENS project, organized by thematic areas. It identifies specific responsibilities across the entire ecosystem—from regulatory authorities and manufacturers to enforcement bodies and vehicle owners. This structure facilitates coordinated implementation while ensuring clear and understandable action items. Each marked cell indicates where specific stakeholder groups should focus their efforts to collectively improve the environmental performance of L-category vehicles.

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Table 4-1: Follow-up and future work considerations after LENS project

Follow-up and future work	Regulators and certification authorities	Vehicle manufacturers	Measurement technology manufacturers	Researchers and academia	Surveillance and enforcement authorities	Vehicle owners	Municipalities
Amendment work for Noise Emissions Type Approval regulations. The UN R41 regulation for motorcycles, R63 for three-wheeled vehicles and R63 for mopeds, should be amended to achieve the following:							
✓ Lower sound limits for L_{WOT}.	X						
✓ Restriction of the sound levels of the ASEP range to avoid sound levels above 85 dB(A) for all engine speeds and load conditions.	X						
✓ Inclusion of all speeds for the ASEP range including start from standstill and speeds above 100 km/h, and the driving conditions recommended by LENS in reports D6.1 and D4.5.	X						
✓ Specification of design to enable inspection friendly detection of tampering and defects, including ECU replacement and flashing, engine speed derestriction and others.	X						
✓ Introduction of RDE for noise emissions in combination with RDE for exhaust emissions.	X						
Amendment work for Pollutant Emissions Type Approval regulations. The UN Regulation 40 and (EU) Nº 168/2013 should be amended to achieve the following:							
✓ Recommendation on gradual RDE testing implementation as an additional test for TA and the establishment of a conformity factor, together with relevant instrumentation development. Real-world driving patterns for high-performance motorcycles cannot be tested in current chassis dynamometers due to technical limitations (e.g. wheel slip), therefore real-world testing is required.	X	X	X	X			
✓ Improve measurement equipment: ○ PEMS and SEMS adaptation to L-category vehicles, in terms of size, weight and accuracy. ○ Improvement of techniques for exhaust flow measurement. ○ Integration of PN measurement requires substantial instrumental development to enable on-road Particle Number measurement capabilities.	X		X	X			
✓ Where RDE is not possible due to equipment size limitation and adaptation to a certain L-subcategory (e.g., small-size L1e-B) then RDC is recommended.	X	X		X			

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Follow-up and future work	Regulators and certification authorities	Vehicle manufacturers	Measurement technology manufacturers	Researchers and academia	Surveillance and enforcement authorities	Vehicle owners	Municipalities
✓ Consideration of real-world driving dynamics observed within the LENS project in order to establish adequate RDE trip requirements and driving dynamics thresholds according to L-subcategories and their characteristics (e.g, PMR). In case it is necessary, implementation of representative RDC.	X	X		X			
✓ Introduce revised WMTC class definition for L3e-A1 vehicles and some L3e-A2 to better reflect real-world driving operation.	X	X		X			
✓ Road load factors not representative for the real-world behaviour. Extra investigation necessary to consider real-world running resistance on the chassis dynamometer	X	X		X			
✓ Introduction of particle number (PN) and particulate mass (PM) limits for all engine types to align with M1 vehicles (passenger cars).	X	X	X	X			
✓ Additionally non-regulated pollutant ammonia (NH_3) should be considered.	X	X	X	X			
✓ Revisit the phase weighting for the different vehicle sub-categories, proposing an application-based phase weighting.	X	X		X			
✓ Specification of vehicle design to enable inspection friendly detection of tampering and defects, including ECU replacement and flashing, engine speed derestriction and others, as well as provisions to prevent tampering or make tampering more difficult.	X	X			X		
✓ CAN access improvement to allow more vehicle information that might be useful to assess exhaust emissions and performance.	X	X					
✓ Better integration between type approval requirements and in-service conformity checks, followed by an adaptation of type approval tests for allowing in-service verification.	X	X					
Amendment of the Environmental Noise Directive and CNOSSOS-EU:							
✓ Update source levels for L-vehicles in the CNOSSOS-EU model taking driving behavior and tampering into account and add a separate dose-effect relationship for L-vehicles to the END, in particular motorcycles. Necessary research work for the dose effect relationship should be performed and the best way to implement this should be investigated.	X			X			X
Implementation of noise camera enforcement on public roads:							
✓ Introduction of Regulations to allow the application and certification of noise cameras together with recommendations on permissible site-dependent threshold sound levels.	X		X	X			X
✓ Develop mobile noise cameras.			X				

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Follow-up and future work	Regulators and certification authorities	Vehicle manufacturers	Measurement technology manufacturers	Researchers and academia	Surveillance and enforcement authorities	Vehicle owners	Municipalities
✓ Run pilot projects to assess effectiveness of enforcement by noise cameras.					X		X
Further investigation of noise and emission control measures on public road:							
✓ Make systematic roadside inspections of LVs compulsory in all EU member states and include - as a minimum - idle emission tests (CO, HC, NOx and PN) and a stationary noise test along with visual tampering detection.					X		X
✓ Where and when appropriate, include an option to carry out pollutant emission and noise measurements from the roadside on passing LVs in conjunction to the roadside inspections.					X		X
Work related to PTI and market surveillance:							
✓ Regulatory frameworks that connect type approval requirements with in-service performance expectations, adapting TA tests for allowing in-service verification.	X	X		X			
✓ Periodic Technical Inspection friendly systems that may soon be mandatory across all EU countries, highlighting accessible placement of emission control and noise reduction components.	X	X					
✓ Standardized diagnostic interfaces for real-world performance verification of both noise and emission systems.	X	X			X		
✓ Standardized inspection protocols and rejection thresholds for in-service emission and noise measurement.	X	X		X			
✓ Data collection systems to monitor real-world performance trends and intervention effectiveness, and feedback mechanisms to inform future type approval requirements.	X	X		X			
✓ Apply market surveillance to reduce availability of parts and services that increase noise and emissions.		X			X		
Awareness campaigns and information resources on the effects of excessive vehicle noise and pollutant emissions and how to control it:							
✓ Implementation and development of add-on devices for existing vehicles to inform drivers of high noise emission.			X	X		X	X
✓ Organisation and follow up of challenges between drivers with the Geco air app in order to help reduce their contribution to noisy and emissive events giving them advice on their driving.			X	X		X	X
Collect and assess EU-wide health and annoyance impact data for L-vehicles by surveys.	X			X	X		X
				X	X	X	X

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Follow-up and future work	Regulators and certification authorities	Vehicle manufacturers	Measurement technology manufacturers	Researchers and academia	Surveillance and enforcement authorities	Vehicle owners	Municipalities
Evaluate implementation of low emission zones for vehicle noise. Improve current requirements of vehicles allowed to enter low emission zone. The requirements applied at the national level generally do not represent real emissions of the fleet [22].				X	X		X
Further research areas ✓ Additional comprehensive testing of specific vehicle types that where underrepresented to evaluate the current fleet or to complement and reinforce actual values ✓ Gather more statistical data of the real-world representative driving behaviour of L-category fleet, including distinction per vehicle type characteristics and intended use. ✓ Investigation of automatic random cycle generation and representative cycles definition for improvement of RDC cycles to be required in TA. ✓ Develop and assess acoustic quantities for detection of tampering and driving behavior. ✓ Despite technical challenges such as aerodynamic noise, mounting and sensors aspects, on-board testing should be explored as a more comprehensive procedure to assess sound levels under a full range of operation conditions on public roads.	X	X		X X X X X	X		

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