LENS L-vehicles Emissions and Noise mitigation Solutions

A LENS on noise and emissions of L-category vehicles

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Cooperation & Funding:

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101056777.

Partners:

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Introduction to the LENS project

LENS has been a three-year Horizon Europe project, which targeted the monitoring of noise and pollutant emissions of L-category vehicles (mopeds, motorcycles, tricycles and quadricycles). The project developed devices and measurement techniques, issued best practices to address emissions, and proposed different policy options for current and future vehicles to reduce emissions.

Such recommendations were issued based on detailed emissions tests of more than 150 vehicles in the laboratory, on the track, and on the road. This document summarises the main findings of the LENS project and outlines policy recommendations.

Environmental noise and air pollution are major concerns worldwide. Within road transport, L-category vehicles make a significant contribution to these issues despite representing only a small share of overall transport activity. The LENS project was envisaged to support authorities, cities, regulators, industry, and citizens in reducing L-vehicle noise and air pollution. To develop a better understanding of the environmental performance of such vehicles, the following research was performed:

- Urban traffic monitoring, driving performance analysis, and simulations to identify high noise and exhaust emission events.
- Development of innovative measurement devices and methods for on-board noise and exhaust emissions characterisation.
- Extensive laboratory and on-road measurement campaigns for noise and exhaust emission of more than 150 L-vehicles.
- In-field surveys, partially combined with roadside inspections, in the cities of Leuven, Paris, and Barcelona, resulted in on-road noise and pollutant emission measurements of an additional 2,300 vehicles.

- Investigation of the practice of vehicle tampering, identifying its prevalence, motivations, and impacts on exhaust emissions and noise.
- Based on the gathered information and data, mitigation solutions were proposed, and an impact assessment was made, including a cost-benefit analysis.
- Finally, policy recommendations for regulations and instruments to reduce noise and exhaust emissions were issued, considering different stakeholders, including regulators, municipalities, and authorities.

L-category vehicles and their typical operational area.
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Measurement technology, methods and data gathering

At the beginning of LENS, high noise and emission events were identified from urban roadside monitoring, simulations, and analysis of available data. These included, among others, high acceleration, start from standstill, engine revving, cold start and deceleration. Some of these events are insufficiently covered by driving cycles in current type-approval regulation, while others are not covered at all. Representative real-world driving patterns for noise testing were defined for manual transmission vehicles, covering these conditions. Such patterns were then compiled into so-called real-world driving cycles that can be used for more representative emissions testing in the laboratory. Further details can be found in LENS deliverables D6.1 'Real-world driving conditions' and D3.5 'Real-world driving patterns to assess LV noise and emissions'.

Development of measurement methods

Assessment of type-approval measurement procedures and findings from investigations of high-emitting operation conditions led to improved methods for measuring exhaust emissions and noise. Exhaust-emission type approval relies on a synthetic driving pattern, the Worldwide Motorcycle harmonised Test Cycle (WMTC) for laboratory tests, while noise type approval is based on pass-by tests on suitable tracks, using specified driving patterns, complemented by wider-operation Additional Sound Emission Provisions (ASEP).

To enable exhaust-emission testing under conditions relevant to real on-road behaviour, LENS proposed the introduction of Real Drive Emission (RDE) procedures, similar to the approach for larger vehicles. LENS also developed highly dynamic real-drive test cycles (RDC) for laboratory use, and noise testing dedicated protocols, informed by the high-emitting driving-condition investigations.

Further detailed aspects of these methods are outlined in deliverable D3.2 'Method and system for on-board noise measurement' and D3.1 'Method and systems for on-board measurement of pollutant emissions.'

BMW motorcycle equipped with portable emission measurement system (PEMS).
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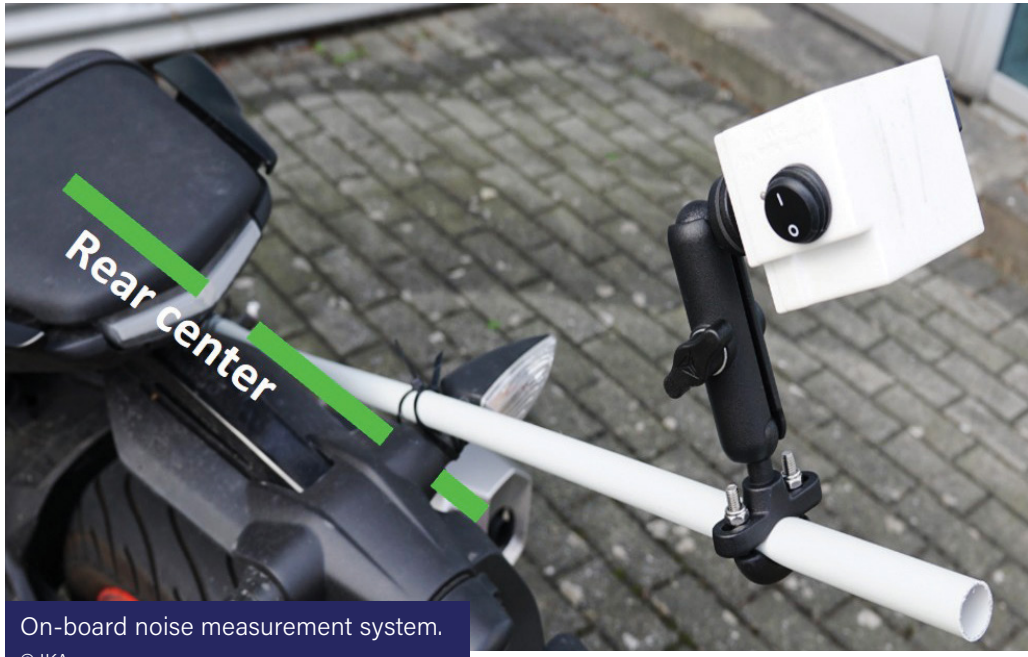
Development of measurement equipment

Based on the insights from the high-emitting driving conditions assessment and the demands from adapted and new measurement methods, LENS developed several novel equipment for the measurement of noise and exhaust emissions, specifically designed for on-vehicle use.

Smart Emission Measurement Systems (SEMS)
Existing Portable Emission Measurement Systems (PEMS), while well-established for passenger cars and heavy-duty vehicles, are unsuitable for RDE testing of small motorcycles or mopeds due to their weight, size and mounting requirements. To address these challenges, the consortium investigated Smart Emission Measurement Systems (SEMS) as more compact alternatives.

SEMS are lighter and easier to mount, although they provide less accuracy compared to full-scale commercial PEMS. They rely on robust sensors rather than high-precision analysers and often omit direct exhaust flow measurements, instead relying on engine parameters from the vehicle's onboard diagnostics (OBD) system to estimate flow while the vehicle is driven on the road. In LENS, hybrid approaches were also deployed, combining SEMS data with laboratory correlation runs or vehicle power modelling to estimate total pollutant mass.

Such specifically adapted SEMS were developed, tested and demonstrated in the project to show their potential for reliable on-board emissions testing. The devices deployed, as well as the measurement protocols, remain in prototype status and are not yet available for commercialisation. LENS experience indicates that further miniaturisation, improved robustness, and better integration with lightweight vehicles will be necessary for large-scale deployment and serving potential regulatory needs.



On-board noise measurement system.
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Particle Number (PN2.5) Sensor

A major ambition in LENS has been the development of a PN2.5 sensor, for on-board measurement of particles down to 2.5 nm. The sensor uses a condensation growth stage together with diffusion charging and electrical detection. Laboratory tests showed that it can detect ultra-fine particles with very high sensitivity. The PN2.5 sensor filled an important measurement gap, as standard condensation particle counters usually detect only particles above 10 nanometres and have a limited concentration range. Although the laboratory results were promising, the PN2.5 sensor is not yet ready for on-road use. Its design requires controlled temperature and flow conditions. This makes it more suitable for validation and calibration work in the laboratory. The project concluded that the concept is technically sound, but the sensor needs more miniaturisation, better stability, and greater robustness before it can be reliably integrated in portable systems. These innovative aspects are explained in deliverable D3.3 'Optimised on-board measurement system including PN2.5 sensor'.

Vehicles with mounted on-road measurement equipment.
Left a category L3e-A3 motorcycle with standard PEMS. © TU Graz/AIP GmbH
Right a category Le3-A1 motorcycle with a SEMS. © TU Graz/Horiba

On-board noise measurement system

Complementing the laboratory-based approach for noise measurements, the LENS project developed an on-board measurement system designed to capture noise data directly during real-world driving. The monitoring system includes a digital Micro-Electro-Mechanical System (MEMS) microphone and a GPS module connected to a compact microcontroller platform. This configuration enables the simultaneous recording of sound pressure levels and positional data, allowing correlations between specific driving conditions and the associated noise emissions.

The on-board noise measurement approach thus complements existing type approval methodologies by capturing data under realistic conditions that cannot be replicated on standardised test tracks. This approach enables a more holistic understanding of L-category vehicle noise behaviour, linking laboratory accuracy with real-world relevance.

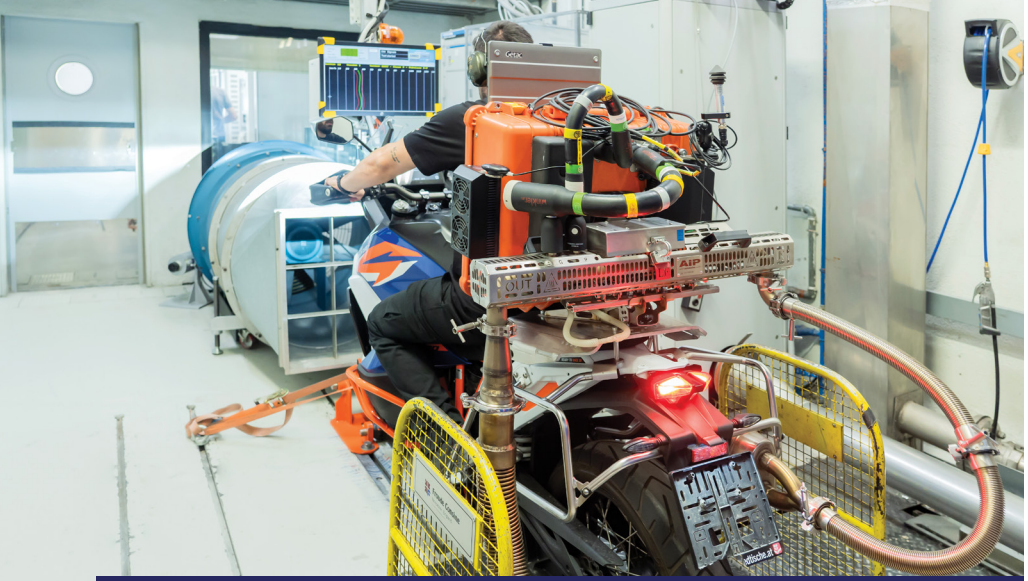
Noise & exhaust emission measurements of 150 vehicles

The assessment of the existing fleet for noise and exhaust emission was conducted by in-laboratory and on-road measurements of noise and exhaust emission. New measurement methods and new equipment were used for the investigation.

Measurements of exhaust emissions

Laboratory tests on 60 vehicles covered type approval and real drive testing in the laboratory to better reflect real-world driving behaviour, determining fleet emissions for regulated and unregulated pollutants and supporting the development of on-road measurement methods. RDE testing assessed L-category vehicles under representative operating conditions; 112 vehicles were examined, with 90 measured on-road and 22 tested under both RDE and type approval conditions, enabling direct comparison of real-world and regulated performance.

Most vehicles met TA limits for regulated pollutants, although certain subcategories, particularly smaller two-stroke L1e-B mopeds, showed high emissions due to limited aftertreatment and transient engine behaviour. Notable levels of



On-road measurement equipment validation with typical 2-wheeler L3e-A3.
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unregulated pollutants, including ammonia and unburned hydrocarbons, were detected, and particle emissions were generally high. Results also showed clear differences between high and low emitters: well-optimised vehicles achieved low emissions, whereas others with less advanced technology or calibration produced elevated levels even in TA tests.

RDE tests consistently produced higher emissions than TA due to more dynamic driving, with particle numbers particularly concerning, as they remain uncontrolled for L-category vehicles. Overall, the findings revealed that laboratory tests underestimate real-world emissions, especially for particles and unregulated gaseous species – in particular ammonia – highlighting the need for strengthened emission control, broader regulatory testing, and greater reliance on RDE data to capture real-world environmental impacts. LENS provided further insights in deliverable D4.4 'Suggested revisions to exhaust emissions TA procedure.'

Measurement of noise emissions

Noise measurements were conducted on 112 vehicles in real on-road conditions: 90 were tested only on-road, 22 under both on-road and type-approval conditions, and 48 solely under type approval. The LENS project demonstrated that on-road noise testing for L-category vehicles is feasible but technically demanding due to variable driving conditions. Results showed higher noise levels in everyday use

Buggy of the L7e-B2 category on a multifunctional test stand.
© IDIADA

than during type approval, with engine speed, load, velocity and rapid acceleration being the main contributors.

Aggressive throttle use, strong acceleration and abrupt braking produced the loudest peaks, with some vehicles exceeding legal limits despite compliance in controlled tests. Variation within classes highlighted the influence of rider behaviour, maintenance and design. While powerful engines were generally louder, some low-powered vehicles produced comparable noise in specific manoeuvres.

Testing on controlled tracks enabled direct comparison with type approval data, confirming that increased load and acceleration raise sound levels. However, the wide variability between vehicles indicated that tighter limits alone would not reduce the most disruptive urban noise events.

Overall, the findings confirmed a clear gap between type-approval noise levels and those produced in real traffic, showing that current procedures capture only part of real-world behaviour. The combined controlled and on-road methods developed in LENS provide a more comprehensive basis for evaluating noise emissions and guiding improvements to regulations, urban noise management and future UN type-approval updates. Further information is provided in deliverable D4.5 'Suggested revisions to TA for noise emission.'

In-field survey on noise and exhaust emission

The in-field surveys assessed the noise and air pollution of passing L-category vehicles involved extensive roadside measurements in real traffic situations across the three city measurement campaigns. Measurements were conducted directly at the roadside over several days, allowing emissions and sound signatures to be observed as vehicles passed in ordinary traffic without interfering with their operation. This approach provides a realistic picture of how a wide range of L-vehicles perform in real-world conditions, and how they differ by location, generation, and user group.

Stakeholder visit of roadside testing in Rueil-Malmaison close to Paris, France. © Niklas Schmalholz

For exhaust emission, the systems captured exhaust plumes from passing vehicles immediately after the tailpipe, from which the concentrations of key pollutants were determined. These included carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM). In parallel, noise monitoring equipment was positioned to capture the sound profile of each vehicle, including its maximum sound pressure level and distinctive sound characteristics.

The field surveys confirmed that, on the one hand, emissions from L-category vehicles have declined substantially as emission standards have become stricter, but they also showed that real-world emissions remain highly variable. This variability arises from factors such as fleet diversity, traffic conditions, and the presence of tampered or poorly maintained vehicles.

In-field survey on noise and exhaust emission test setup in the Belgian city of Leuven. © Niklas Schmalholz

Study on tampering, including field tests for noise & exhaust emission

Tampering is generally defined as any form of modification carried out by a vehicle user that places the vehicle outside its original type-approved specifications. These alterations, ranging from exhaust and engine control changes to air intake and fuel system adjustments, frequently worsen pollutant and noise emissions. The practice contributes to environmental degradation and public health risks across the EU.

L-vehicle user survey on tampering

LENS partners gathered responses from over 500 vehicle owners across more than 20 EU countries, supported by 64 interviews in Greece. Participants were mostly middle-aged men, typically owning motorcycles registered after 2007, with street, naked, supersport and superbike models comprising nearly half the sample. Most vehicles were bought second-hand and used mainly for leisure.

The survey showed widespread, multi-layered tampering. Common changes included replacing silencers with aftermarket units, modifying air filters, fairings and engine-control software, and removing silencers or catalysts. Over a third of all alterations affected the exhaust system, with many others involving the electronic control unit and air intake.

Nearly half of respondents modified their vehicles to increase power, while others sought louder sound, aesthetic gains or improved handling. Most modifications were owner-performed, though workshops carried out nearly a third, and changes were generally permanent.

Consistent responses across countries indicated that tampering is widespread throughout Europe. The deliverable D5.1 ‘LVs tampering and undesirable effects’ provides further insights into the survey data and its assessment.

In-field tampering measurements

In-field surveys were carried out in three different EU countries to identify tampered vehicles and measure noise and tailpipe emissions. Whereas the first in-field emission test took place in an urban environment of the Belgian city of Leuven,

the second was conducted in the two French communes of Rueil-Malmaison, a Parisian suburb, and Dampierre-en-Yvelines, a destination for motorcyclists in the Paris Metropolitan region. The third test took place at a busy arterial road in Barcelona, Spain.

The proportion of vehicles identified as tampered in Leuven and Barcelona was strikingly similar, at approximately 10%. The most altered components were the exhaust system and the muffler. The modified or tampered L-vehicles displayed several distinctive characteristics. Around 50% of the 2-strokes pulled over were tampered with, in contrast to only 9% of the 4-strokes. On average, the engines of the tampered vehicles were also considerably larger, with an average capacity of 446 cm^3 versus 285 cm^3 in non-tampered vehicles.

Moreover, these vehicles tended to be older, with an average age roughly two years greater than their unmodified counterparts. Despite these notable differences in engine type, size and age, there were no significant variations in terms of Euro emission class or overall vehicle mileage between the two groups. More information is provided in the deliverable D5.3 ‘Results of field surveys on LV tampering.’

Road-side inspection procedure (Leuven campaign).
© Åke Sjödin

Mitigation solutions and impact assessment

Scenarios

Five main scenarios of potential mitigation solutions to reduce noise and exhaust emissions were identified and simulated through modification of the emission factors, the fleet, or vehicle use to assess their impact:

Besides these scenarios, it was also found that sound emission levels in the EU CNOSSOS model for noise mapping are too low and therefore need to be updated to properly take L-vehicles into account.

1.	Strengthening type-approval regulations for noise and pollutant emissions, including real driving emissions testing.
2.	Reducing illegal vehicle modifications (tampering) by vehicle checks through roadside and periodic technical inspections, including automation, digital tools and market surveillance.
3.	Local regulations: speed limits and enforcement to limit loud and polluting driving behaviour.
4.	Access restrictions for loud and high-emission vehicles in specific areas or roads, including low-emission zones for noise.
5.	Accelerated fleet renewal: Incentives for the faster replacement of older vehicles by electric or less polluting models.

Impact Assessment

The scenarios were assessed for 2025–2050 and compared with the 2025 baseline, which included two electrification cases: one with 17% electric L-vehicles by 2050 and another with 50%. Using data from measurement studies, emission factors for noise and exhaust emissions were created with two main tools. PHEM was used for detailed 1 Hz simulations of exhaust, brake and tyre emissions for all vehicle types and driving conditions. For noise, LENS used the TRANECAM model, a European tool often applied in noise planning and regulation. These emission factors were then used in COPERT to estimate emissions for the European L-vehicle fleet under typical use.

For pollutant emissions, the introduction of RDE testing delivers the largest cuts. By 2050, NOx cuts reach 28 kt in the high-electrification case and 41 kt in the low-electrification one. Fleet renewal also helps, especially with high electrification. Anti-tampering measures can lower long-term sound exposure (Lden) by up to 2 dB(A) in Southern Europe, while behaviour-related measures can reduce single noise events by 3 dB or more. Access restrictions provide the biggest reductions, up to 5.3 dB(A) for Lden and over 10 dB for single events. Driver awareness and digital tools such as the Geco Air app can further support better driving behaviour and reduced emissions. A detailed description of the scenarios and the app is available in deliverables 6.2 'Case-studies-intervention options', and in D6.3 'Eco-mobility app for best practices on LV use.'

Cost-benefit Analysis

An exploratory cost-benefit analysis showed that scenarios that affect the existing fleet are generally cost-effective and can be implemented in the short term. Measures to reduce tampering are most cost-effective, together with access restrictions. As improved UN Regulations only affect new vehicles, it takes many years to produce benefits on a larger scale. Accelerated fleet renewal is also a long-term instrument and requires state subsidies, but has benefits in both noise and emissions, especially if tampered and older vehicles are replaced. More on the cost-benefit can be found in the deliverable D6.4 'Impact of interventions in decreasing LV noise and pollutant emissions.'

LENS recommendations

The following recommendations are based on the LENS research results and expertise of all LENS partners, as well as exchanges with external experts, public authorities, and citizens' initiatives. LENS partners stress that the following list is not ordered by priority or importance. A detailed version of the technical aspects of the recommendations is available in deliverable D6.5 'Recommendations for quieter and cleaner LVs'.

- **Introduction of RDE and harmonised type-approval testing**
  European institutions must focus on progressively strengthening emission control framework for L-category vehicles. The key priority is implementing Real Driving Emission (RDE) testing for LVs, as miniaturised Portable Emission Measurement Systems (PEMS) or Sensor Emission Measurement Systems (SEMS) become technically reliable. Additionally, authorities could implement representative Real Driving Cycles (RDC) in laboratory testing, when necessary, alongside a revised WMTC Class definition and WMTC phase weighting to better reflect actual usage patterns.

- **Extend pollutant coverage in emission standards and build a unified EU Digital Governance System**
  Regulatory frameworks should include exhaust Particle Number and Ammonia metrics to reduce health and environmental risks associated with these pollutants. More specifically, the current regulation of PN emissions from passenger cars – with proper adaptations – should be adopted. Furthermore, establishing an EU-level digital emissions governance system would create a unified database aggregating data from RDE testing, Periodic Technical Inspection (PTI) results, and remote sensing campaigns, enhancing monitoring capabilities.

- **Comprehensive revision of UN noise regulations for L-vehicles and PTI consideration**
  Current UN type-approval regulations for L-vehicle noise do not yet capture all driving conditions that produce excessive noise levels. The additional sound emission provisions (ASEP) should be amended to include high noise at all relevant speeds and driving conditions, limits for acceleration noise should be tightened to avoid excessive sound levels, and RDE should be introduced. Consideration of more effective in-service verification during type-approval, practical PTI measurement methods and clearer rejection thresholds are also needed. Type approval procedures and in-service conformity checks should be better aligned to ensure vehicles maintain compliance throughout their lifecycle. This integration should include adapting type approval tests to facilitate straightforward in-service verification for PTI and roadside inspections.

- **Enhance the Environmental Noise Directive to accurately reflect the impact of L-vehicles**
  The Environmental Noise Directive, particularly the CNOSSOS-EU model for noise mapping, should be improved to better reflect the sound emission and impact of loud vehicles by amending their source sound levels and dose-effect relationships. This could help trigger local noise action plans. Annoyance, sleep disturbance and health impacts of L-vehicle noise should be surveyed in relation to single events and assessed at the national and EU level to better quantify the impact as a basis to amend EU legislation and national and local interventions.

- **Increase EU funding for advanced emission and noise measurement technologies**
  EU institutions should strengthen support to Member States through targeted funding for projects that accelerate the development of robust on-road emission measurement technologies, improve the integration of remote sensing and noise cameras into enforcement frameworks, and modernise Periodic Technical Inspection (PTI) systems to include emission and noise testing.

- **Specification of vehicle design to enable inspection-friendly detection of tampering and defects**
  L-vehicle manufacturers should extend on-board diagnostic (OBD) access to provide more comprehensive vehicle information for assessing exhaust emissions and performance throughout standardised diagnostic interfaces. Vehicle design should consider PTI and roadside inspection requirements, ensuring easy access to emission control and noise-relevant components.

- **Implement EU-wide labelling and approval systems for vehicles and after-market parts**
  Every new L-vehicle should display clear labelling showing its emission class and certified noise level. The EU should establish a central approval system for aftermarket components that applies to the same standards as original equipment, with only certified parts permitted for sale and listed in a public registry.

- **Integrated design approach for consistent environmental integrity**
  Manufacturers should ensure vehicles maintain environmental performance throughout their life cycle, not just at certification. This requires designing compliance into vehicle systems to maintain emissions within approved levels throughout the vehicle's useful life. Additionally, manufacturers should implement integrated design approaches combining advanced control technologies with tamper-resistant features such as secure ECUs and traceable diagnostics.

- **R&D on measurement technology and regulatory innovation**
  Research efforts should focus on advancing measurement technology (PEMS and SEMS systems) to enable RDE introduction. For noise testing, on-board methods should be explored as a more comprehensive procedure. Dedicated acoustic quantities and machine learning techniques should be developed to detect tampered vehicles and those with loud and high-emission driving behaviour.

- **Gather more statistical data of the real-world representative driving behaviour of the L-category fleet, including distinctions per vehicle type characteristics and intended use**
  Researchers should conduct comprehensive testing of underrepresented vehicle types to better evaluate current fleet performance. This should include a distinction between vehicle characteristics and intended use. Additionally, EU-wide health and annoyance impact data for L-vehicles should be collected through standardised surveys.

- **Standardise L-vehicle testing methodologies across the EU and introduce on-board monitoring**
  National testing facilities should be formally recognised as integral to the European vehicle compliance ecosystem, providing certification services and technical support for enforcement agencies. Integrating on-board monitoring data into the testing process would enhance the detection of illegal modifications.

- **Implement effective urban access regulations and low-emission zones**
  Cities should prevent high-pollutant vehicles from entering urban areas through modernised access regulations that reflect both emission and noise performance. Current low-emission zone requirements should be enhanced to better represent real-world fleet emissions.

- **Implement systematic roadside inspection and testing programs in urban areas**
  Member states should introduce systematic roadside inspections of L-category vehicles. These inspections should include comprehensive idle emission tests measuring carbon monoxide, hydrocarbons, nitrogen oxides, and particle number, alongside standardised stationary noise tests. Inspections should also incorporate visual examinations and diagnostic tools specifically designed to detect tampering of emission control and noise reduction systems.

- **Deploy advanced monitoring and intelligent enforcement systems**
  Municipal and regional authorities should invest in advanced monitoring and enforcement technologies throughout, including remote sensing systems capable of detecting both emission and noise irregularities from passing L-vehicles, identifying polluting or tampered vehicles, and noise psychoacoustic characteristics. Automated enforcement, such as mobile or fixed noise cameras, should complement data-driven analytics that distinguish between natural vehicle ageing and deliberate tampering. These advanced indicators help enforcement agencies identify illegal modifications and excessive sound while providing valuable input for urban planning to create quieter traffic routes and acoustic comfort zones.

- **National financial incentives to accelerate fleet renewal**
  Authorities should introduce financial incentives encouraging owners to replace older, high-emission models with Euro 5/5+ compliant or electric vehicles. Scrappage schemes offering compensation or tax benefits are particularly effective for withdrawing old vehicles, provided certification systems prevent outdated vehicles from re-entering circulation.

- **Promotion of eco-driving applications and incentives**
  Cities and governments should encourage better driving habits through eco-driving applications, such as GECO Air, that reward efficient and quiet riding styles. Apps that provide feedback on acceleration, braking, and fuel use can be integrated into insurance schemes, municipal incentives, or community challenges to normalise responsible riding behaviour.

- **Promote and combine targeted enforcement with educational initiatives**
  Communication campaigns should highlight both the practical disadvantages of tampering and loud driving behaviour, including higher fuel costs, reduced engine lifespan, and potential insurance issues, and its environmental impact. Emphasising the social unacceptability of tampering and loud driving can gradually shift cultural norms within rider communities.

Design and layout:
Pitch Black Graphic Design, The Hague/Berlin

Cover photos:
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Cooperation & Funding:

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101056777.

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