



# A LENS on noise and emissions of L-category vehicles

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## Partners:



# Introduction to the LENS project

LENS was a three-year Horizon Europe project that focused on monitoring noise and pollutant emissions from 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. Despite their relatively small size, L-category vehicles contribute to road transport noise and emissions, with their impact varying by driving behaviour, vehicle type, age, and condition. 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, were conducted in the cities of Barcelona, Leuven, and Paris, resulting 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.



L-category vehicles and their typical operational area.

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# Measurement technology, methods and data gathering

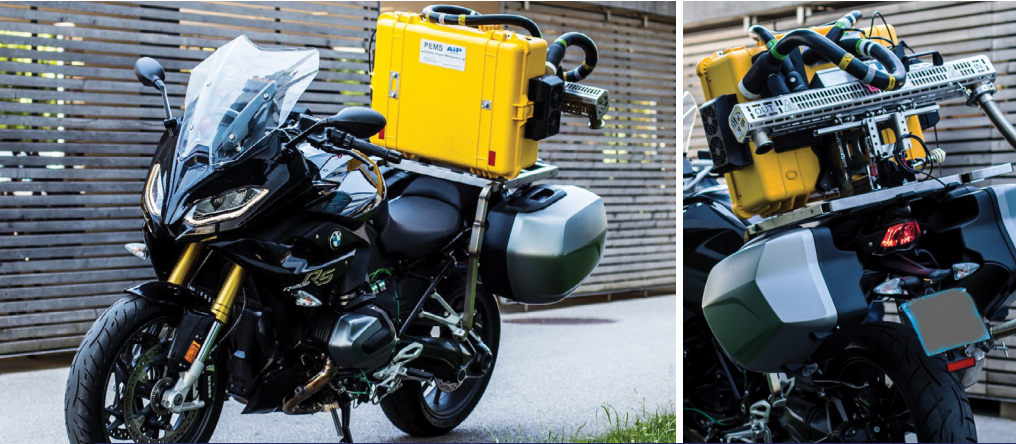
At the beginning of LENS, high noise and emission events were identified from urban roadside monitoring, simulations, and analysis of available data. These included, among others, high acceleration, start from standstill, engine revving, cold start, and deceleration. Some of these events are insufficiently covered by the current type-approval regulation's driving cycles, 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 laboratory emissions testing. 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. In contrast, 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 introduced tests following Real-Drive Emission (RDE) procedures, adapting the approach used for passenger cars, in parallel with laboratory bench tests. LENS also developed highly dynamic real-drive test cycles (RDC) for laboratory use and dedicated noise-testing protocols, informed by high-emitting driving-condition investigations.

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



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

© Stephan Schmidt

## 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 pieces of 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 not suitable for RDE testing of all types of motorcycles and 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, but they offer less accuracy than full-scale commercial PEMS. They rely on robust sensors rather than high-precision analysers and often omit direct exhaust flow measurements, instead using engine parameters from the vehicle's onboard diagnostics (OBD) system to estimate flow while the vehicle is 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.

© IKA

### Particle Number (PN<sub>2.5</sub>) Sensor

A major ambition in LENS has been the development of a PN<sub>2.5</sub> sensor for on-board particle measurement down to 2.5 nm. The sensor developed uses a condensation growth stage, diffusion charging, and electrical detection. Laboratory tests showed that it can detect ultra-fine particles with very high sensitivity. The PN<sub>2.5</sub> 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 PN<sub>2.5</sub> sensor is not yet ready for on-road use. Its design requires controlled temperature and flow conditions. This makes it more suitable for laboratory validation and calibration work. The project concluded that the concept is technically sound, but the sensor needs further miniaturisation, improved stability, and greater robustness before it can be reliably integrated into portable systems. These innovative aspects are explained in deliverable D3.3 'Optimised on-board measurement system including PN<sub>2.5</sub> 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.

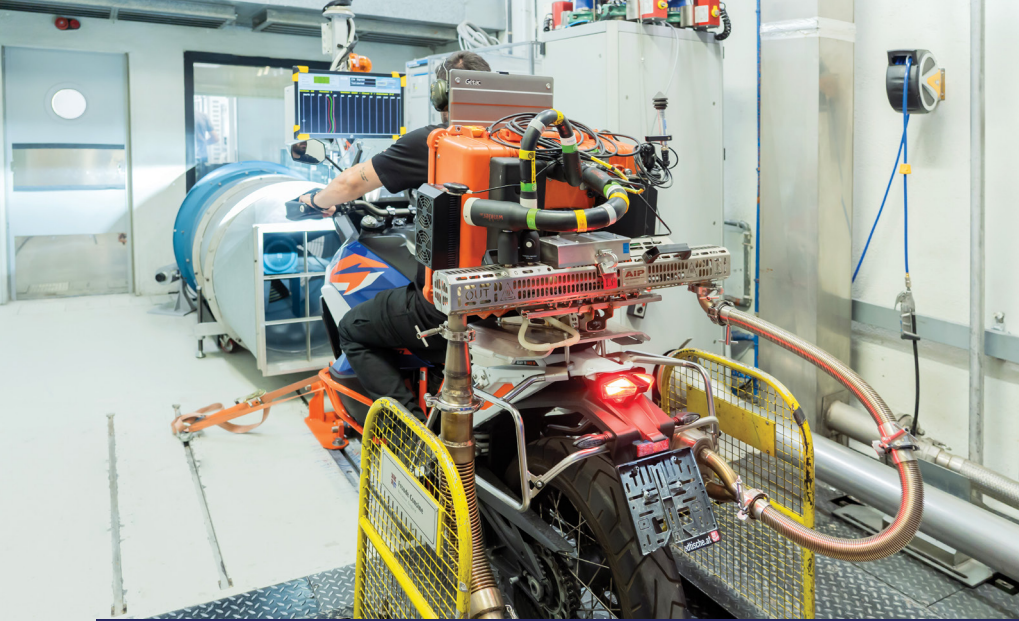
The on-board noise measurement approach thus complements existing type-approval methodologies by capturing data under real on-road conditions. Although such an approach requires further development, it still provides a useful bridge between type-approval roadside measurements and operation conditions that may be difficult to capture in such type-approval tests.

## Noise & exhaust emission measurements of >150 vehicles

The assessment of the existing fleet for noise and exhaust emissions was conducted through in-laboratory and on-road measurements. 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-world driving testing to better reflect real-world driving behaviour, determined fleet emissions for regulated and unregulated pollutants, and supported the development of on-road measurement methods. RDE testing assessed L-category vehicles under representative operating conditions; 112 vehicles were examined, including 90 measured on-road and 22 tested under both RDE and type-approval conditions, enabling direct comparison of real-world and regulated performance. The tested vehicles were selected to cover all L-sub-categories and vehicles falling in the emission classes EU5+, EU5, EU4, and older. All vehicles were in a used but road-safe status; to assess the influence of tampering, some vehicles with obvious tampering measures were included. Details on the vehicle classification are given in Deliverable 4.2 'Exhaust emission data from laboratory tests.'



On-road measurement equipment validation with typical 2-wheeler L3e-A3.

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Most vehicles met TA limits for regulated pollutants, although certain sub-categories, particularly smaller two-stroke L1e-B mopeds, showed high emissions due to simplified emission control and highly transient engine behaviour. Notable levels of 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.

For those vehicles tested with PEMS, or SEMS developed by the consortium, RDE tests consistently revealed higher levels of regulated pollutants than TA, due to more dynamic driving, with particle numbers particularly concerning, as they remain unregulated for L-category vehicles. Overall, the findings revealed that laboratory tests conducted in LENS generally underestimated real-world emissions of regulated and unregulated pollutants, such as particles and 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.'



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

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### 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, given variable driving conditions. Results showed higher noise levels in everyday use 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, which exceeded measured levels in TA 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 a 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 that 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

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

© Niklas Schmalholz



wide range of L-vehicles perform in real-world conditions, and how they differ by location, generation, and user group.

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 (NO<sub>x</sub>), 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, and, on the other hand, 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 illegal 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 face-to-face 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 catalyts. Over a third of all alterations affected the exhaust system, with many others involving the electronic control unit and air intake.

Nearly half of the 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 of them, 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 conducted in three EU countries to identify tampered vehicles and to 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<sup>3</sup> versus 285 cm<sup>3</sup> in non-tampered vehicles.

Moreover, these vehicles tended to be older, with an average age roughly 2 years greater than that of their unmodified counterparts. Despite notable differences in engine type, size, and age, there were no significant differences in Euro emission class or overall vehicle mileage between the two groups. More information is provided in 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:

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.

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

## 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 to conduct 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, NO<sub>x</sub> 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(A) or more. Access restrictions provide the biggest reductions, up to 5.3 dB(A) for Lden and over 10 dB(A) 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 D6.2 '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 when combined with access restrictions. As improved UN Regulations do not affect the existing fleet, they only affect new vehicles, and it takes many years to produce benefits on a larger scale. Accelerated fleet renewal is also a long-term instrument that requires state subsidies but offers benefits in both noise and emissions, especially if tampered and older vehicles are replaced. More on the cost-benefit analysis can be found in deliverable D6.4, 'Impact of interventions in decreasing LV noise and pollutant emissions'.

# LENS recommendations

The following recommendations are based on a synthesis of LENS research results, the technical expertise of all LENS partners, and exchanges with external experts, public authorities, and citizens' initiatives during the lifetime of the project. These recommendations are not ordered by priority or importance. Details on the technical aspects of the recommendations can be found in deliverable D6.5 'Recommendations for quieter and cleaner LVs' and throughout the various technical deliverables of the project.

## Improve Regulations

### ► Introducing RDE and harmonised type-approval testing

European institutions must progressively strengthen the framework for controlling emissions from L-category vehicles. Implementing Real Driving Emission (RDE) testing for LVs can be considered, as miniaturised Portable Emission Measurement Systems (PEMS) and Sensor Emission Measurement Systems (SEMS) may become technically available for type approval testing with moderate development work. Laboratory bench testing can be further improved by revising the WMTC and/or introducing Real Driving Cycles (RDCs) to reflect actual usage patterns better. Finally, both the WMTC Class definition and the WMTC phase weighting should be reviewed to reflect recent developments in vehicle performance better.

### ► Extending pollutant coverage in emission standards

Particle Number and ammonia limits need to be considered in any upcoming emission standards to provide more thorough health and environmental control of L-category vehicle emissions. Introducing the current regulation on PN emissions from larger vehicles, with appropriate adaptations, appears to be a priority in this direction.

### ► Comprehensively revising UN noise regulations with consideration of Periodic Technical Inspection (PTI)

UN type-approval regulations for L-category vehicle noise should continue to be reviewed and updated to cover as wide a range of operation conditions as possible. Sound levels during accelerations and other individual operating conditions are often critical, as revealed by on-board sound-emission measurements. Methods for in-service verification and mandatory sound-emission level checks during PTI could also be considered.

### ► Specifying vehicle design to enable inspection-friendly detection of tampering and defeat devices

Relevant developments in on-board diagnostic (OBD) technologies for passenger cars could be considered for L-category vehicles as well, to improve access to vehicle information and provide a more thorough assessment of emissions-related data. Also, vehicle design-relevant requirements could be issued to reduce the likelihood of vehicle tampering and enable easier monitoring of vehicle status during PTI and roadside tests.

### ► Enhancing 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 levels to better quantify the impact, as a basis for amending EU legislation and for national and local interventions.

### ► Enhancing labelling for aftermarket parts

Procedures to improve the labelling of legal aftermarket components and clearly distinguish them from potential illegal modifications can be improved.

### ► Ensuring environmental integrity over the vehicle's entire lifetime

Environmental performance should be maintained throughout the vehicle's lifetime. Updated statistical data on vehicles' useful life should be collected, and durability requirements should be revisited accordingly.

## Improve Monitoring

### ► **Supporting advanced emission and noise measurement technologies in the field**

Projects that accelerate the development and demonstration 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 should be properly funded and supported by the EU, national, and local authorities.

### ► **Supporting R&D on measurement technology**

Research efforts should focus on advancing measurement technology (PEMS and SEMS systems) to enable the introduction of RDE for L-vehicles. For noise testing, on-board methods should be considered a more comprehensive approach than type-approval and should be further explored. Dedicated acoustic metrics and machine learning techniques should be developed to detect tampered vehicles and those exhibiting loud, high-emission driving behaviour.

### ► **Gathering statistical data of the real-world representative driving behaviour of L-sub-categories**

A diverse range of operating conditions, operating frequencies, and usage patterns is associated with the different L-sub-categories. Better statistics from fleet vehicles are needed to design more effective policies for monitoring and controlling their performance. Additionally, EU-wide health and annoyance impact data for L-vehicles should be collected through standardised surveys.

## Improve interventions

### ► **Implementing effective urban access regulations and low-emission zones**

By using advanced technologies to monitor on-road pollutant and sound emission levels of vehicles, authorities can take measures (access control, call-in for technical inspection, etc.) for those vehicles that are consistently monitored to exhibit excessive sound and emission levels. Technical guidance procedures are required to avoid excessive false positives (errors of commission) that would jeopardize the cost-effectiveness of such testing.

### ► **Implementing systematic roadside inspection and testing programs in urban areas**

Roadside inspections of L-category vehicles can be used to detect high-emitters and illegal modifications and require specialised staff working in collaboration with the authorities. The potential of simplified procedures to indicate high emission levels needs to be explored. The use of electronic diagnostic tools specifically designed to detect tampering of emission control and noise reduction systems can also be considered.

### ► **Providing financial and other incentives to accelerate fleet renewal**

Authorities could introduce financial and other (e.g., access) incentives to encourage the replacement of older vehicle types with newer models equipped with the latest emission-control technology. Scrappage schemes offering compensation or tax benefits are particularly effective for withdrawing old vehicles, provided certification systems prevent outdated vehicles from re-entering circulation.

### ► **Promoting eco-driving applications and incentives**

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

► **Promoting and combining 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.

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Motorcycle with mounted on-road measurement equipment.  
Category Le3-A1 motorcycle with a SEMS. © TU Graz/Horiba

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