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L-vehicles Emissions and Noise mitigation Solutions

D5.1 L-vehicle tampering and undesirable effects

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Revisions table

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Executive summary

This deliverable document focuses on L-vehicle tampering and the negative consequences that it may have on air and noise pollution. More specifically, it aims to describe the most common methods of L-vehicles tampering currently applied within the European Union and assess their undesirable effects on both pollutant and noise emission levels. Various methods were used, including literature review, utilization of own information, and questionnaires, in order to create an effects table that documents the impacts of tampering on pollutant and noise emission levels by using a qualitative approach. This table may be used as a guide, with the purpose of identifying different tampering types more easily and reducing any negative effects of L-vehicles operation on both air and noise pollution. The current document will be submitted as the deliverable document “D5.1 L-vehicle tampering and undesirable effects”.

List of Abbreviations

CO_2	Carbon dioxide
CO	Carbon monoxide
EU	European Union
HC	Hydrocarbons
HEU	Horizon Europe
LENS	L-vehicles Emissions and Noise mitigation Solutions
LVs	L-category Vehicles
NO_x	Nitrogen oxides
OEM	Original Equipment Manufacturer
WP	Work Package

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1 Introduction

1.1 Background

The operation of L-category vehicles (LVs: mopeds, motorcycles, tricycles, and quadri-mobiles) contribute to numerous harmful effects on both air and noise pollution, due to – historically – more relaxed emission standards than other vehicle categories. Besides pollutant emissions, they are a known source of noise annoyance since their peak sound levels and general sound characteristics are distinct compared to those of other types of vehicles. Such negative effects of LVs operation are particularly manifested for tampered vehicles. According to the EU, tampering refers to "inactivation, adjustment or modification of the vehicle emissions control or propulsion system, including any software or other logical control elements of those systems, that has the effect, whether intended or not, of worsening the emissions performance of the vehicle" [1]. Such modifications may be the removal or replacement of the silencer to alter the sound behavior of the vehicle or the manipulation of the engine control unit (ECU) to alter its powertrain performance. However, these changes often take place without considering the possible negative consequences to emission and noise levels. Anti-tampering measures must be taken with a view to preventing such modifications and decreasing these detrimental effects.

This report is part of Work Package 5 and constitutes the deliverable of Task 5.1 of the L-vehicles Emissions and Noise mitigation Solutions (LENS) project, funded from the European Union (EU)'s Horizon Europe (HEU) research and innovation programme under grant agreement No 101056777. LENS is a three-year HEU project with the main aim to assist enforcement authorities, cities, and regulators to decrease the contribution of LVs to both noise and air pollution. It develops and promotes interventions and best practices to address light vehicles' noise and pollutant emissions. It also makes suggestions for regulatory initiatives that could lead to the improvement of the performance of future vehicles, including the control of emissions under real-life driving conditions and the enforcement of anti-tampering measures.

1.2 Objective

This report aims to describe the most common LVs tampering practices that are currently taking place around the EU and to assess their impacts on both air and noise pollution. More specifically, the methods used to assess such effects comprise a literature review, utilization and building on own information and judgement, and conducting interviews, using specially designed questionnaires. A qualitative approach is used to evaluate the effects that different tampering methods may have not only on pollutants, but noise emission levels as well, in the form of a summary effects table. It is documented whether an increase or decrease is observed on the emission levels after applying each tampering practice, or whether such a practice has negligible effects. The result of this work could therefore be used as a guide to identify tampering methods easier and to reduce the detrimental effects of LVs on air and noise pollution.

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1.3 Structure

Following this introduction, chapter 2 describes the methods and the selected approaches applied. Chapter 3 describes the general problem of tampering and the most common methods of LV tampering at EU wide scale. Chapter 4 presents the results from the questionnaires that were completed in different EU countries as part of the LENS project and assesses the undesirable effects of the most common LV tampering techniques in the form of an effects table. Subsequently, chapter 5 provides the conclusions that can be drawn from the present work. More detailed information about the questionnaire responses and results is included in the appendix.

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2 Methods

In this chapter the methodology that was used to complete this work is described. It was possible to retrieve the required information from various sources. These included a literature review, utilization of own information, online questionnaires, and face-to-face interviews with Original Equipment Manufacturers (OEMs), service shop owners, and LVs owners and enthusiasts from different EU countries.

Various published papers [2 to 8] related to LVs tampering were reviewed, as well as reports from previous projects [9 to 16] on an EU wide scale. Quantitative data regarding the observed changes in air pollutants and noise level emissions before and after implementing different tampering techniques were collected and classified, in order to be translated to qualitative effects.

The project partners' expertise was also included. Each partner organization contributed to this work with their experience related to the effects of LVs tampering.

In total, 602 online questionnaires were completed within the EU and 64 in-person interviews took place in Greece. The target group was people that own and have implemented at least one modification to their LV. The completion of the questionnaires and the interviews was on a voluntary basis. The whole process was transparent, and all the people involved were informed about the objectives of the LENS project. This happened either in the beginning of each interview by the reporter, or by a written message describing the project in the introduction of the online questionnaires.

The responses from both online and face-to-face questionnaires were gathered and post-processed to identify the most common tampering methods. From the review of the responses, it was also possible to evaluate the influence of various characteristics, such as the age of the vehicle owner or the vehicle category, on tampering.

After the collection of the available data from all the above-mentioned sources, a detailed table was created, and each tampering method was categorized. The categorization was done depending on the system of the vehicle that each method was aiming to modify. In this way, it was possible to check the consistency of the findings originating from different sources and, consequently, draw some conclusions and evaluate the health and environmental effects of LVs tampering using a qualitative approach.

In the following subsections, more details are given concerning each different type of source of information.

2.1 Literature review

Previous studies that focused on LVs or tampered vehicles and tested various tampering methods to assess their impacts on air and/or noise pollution were reviewed. It was possible to retrieve quantitative data regarding the observed changes in pollutants and noise level emissions before and after implementing a tampering technique on various LVs. The data was then processed in order to draw some qualitative results on LVs tampering effects on air and noise pollution. The results of this review are presented in chapters 3 and 4, where relevant. It is worth mentioning that, in most cases, the tested vehicles were restored to their original states after completing the tests.

2.2 Own information

It was necessary to use own information and knowledge gained from experience, for instance by reviewing reports from previous projects or papers concerning tampered LVs led by partner organizations. In addition,

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project partners' (IVL, TNO, KU LEUVEN, KTM, BMW, PIAGGIO, DUCATI & subcontractor Heinz Steven) contribution with their experience and expertise was crucial for the completion of this work. In addition, all project partners contributed by encouraging people from various EU countries to participate in the online questionnaires that were specifically created to assess the current situation regarding tampering practices in the EU.

2.3 Questionnaires

In total, 602 online questionnaires were completed within the EU. 520 of them were completed in English and 82 of them in Greek, as a version translated to Greek was used targeting Greek people. The objectives of this survey were to assess the current situation regarding tampering practices at EU wide scale, identify the most common methods of LVs tampering and find out how frequently these take place in different European countries.

The target group was LVs owners and enthusiasts that regularly use or own a motorcycle, or another LV, and had tampered their vehicle at least once. Motorcycle enthusiasts and clubs were approached via social media pages and groups, platforms, and sites, in order to fill out online Google forms.

The questionnaires were voluntary and the whole process was transparent. All participants were informed about the objectives of the LENS project by a written message describing the project in the introduction of the online questionnaires (see Figure 1). Links to the official webpage and social media pages of LENS were also provided for whoever would be interested in further information of the project. All gathered data was anonymized and was used only within the scope of the LENS project. The personal data required from the participants were only their age, sex, and country of residence for the sake of taking conclusions for the project.

The questions referred to vehicle characteristics, such as the brand and type, engine capacity, year of registration, usage, as well as information about any tampering attempts and the reasons behind them. Even though the questionnaires were specifically targeting owners of tampered vehicles, in 157 questionnaires there was no mention of any modification. These responses were not included in the analysis. Hence, only 445 of the 602 responses were further reviewed and assessed.

A problem that arose in this process was that quite often people were not willing to share this kind of information, although it was clarified that no personal information would be shared with law enforcement of any kind. They were in all probability concerned that the provided information would be used at the expenses of themselves, for instance so as to enact stricter legislation and impose new fines regarding tampered vehicles. A measure taken to overcome this problem was to directly contact the leaders or coordinators of different motorcycle enthusiasts' groups and ask them to forward the questionnaires themselves to their group members/partners, as they would more easily trust them. Thanks to the measures taken and the valuable contributions of the project's partners in various EU countries, eventually it was possible to reach a significant number of reliable responses for such a controversial question.

The results of the analysis of the questionnaires are presented in chapter 4.1, while more detailed information about the questions and responses is given in the Appendix.

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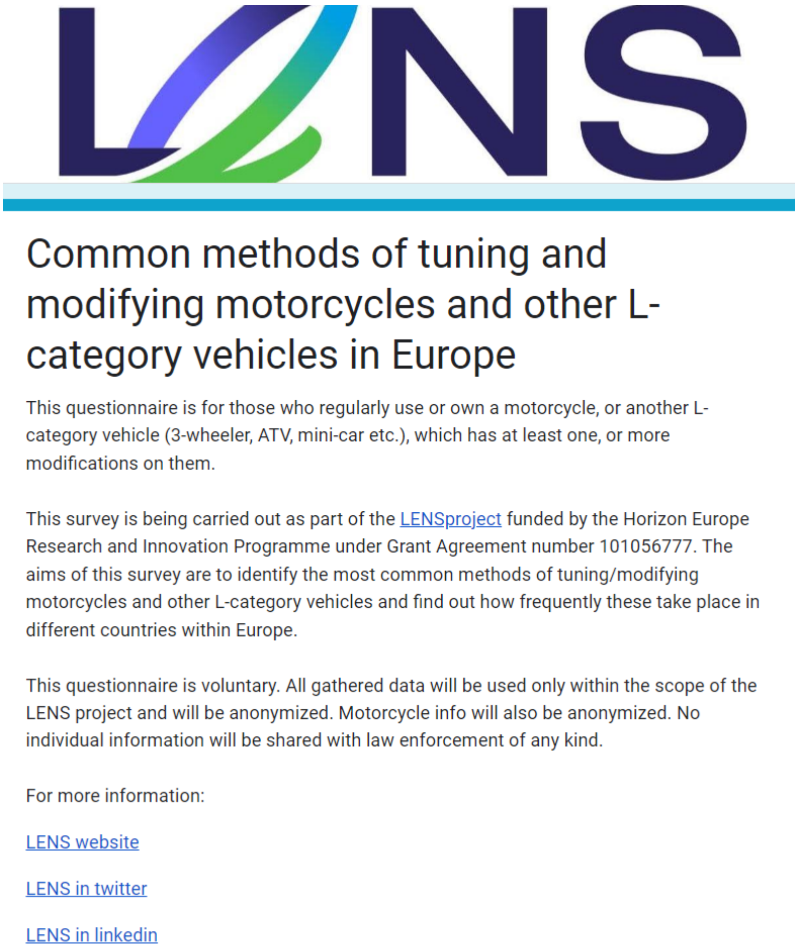
Common methods of tuning and modifying motorcycles and other L-category vehicles in Europe

This questionnaire is for those who regularly use or own a motorcycle, or another L-category vehicle (3-wheeler, ATV, mini-car etc.), which has at least one, or more modifications on them.

This survey is being carried out as part of the LENSproject funded by the Horizon Europe Research and Innovation Programme under Grant Agreement number 101056777. The aims of this survey are to identify the most common methods of tuning/modifying motorcycles and other L-category vehicles and find out how frequently these take place in different countries within Europe.

This questionnaire is voluntary. All gathered data will be used only within the scope of the LENS project and will be anonymized. Motorcycle info will also be anonymized. No individual information will be shared with law enforcement of any kind.

For more information:

LENS website

LENS in twitter

LENS in linkedin

Figure 1: Introduction to the online questionnaire used in the scope of the LENS project.

2.4 Interviews

In total, 64 in-person interviews with repair shop owners, motorcycle owners and enthusiasts, and online motorcycle sellers took place in Greece. In some cases, the latter were contacted by phone. Three of the interviewees did not mention any modification to their vehicle and their responses were therefore excluded from the analysis. Hence, 61 physical questionnaires were reviewed further.

As for the online questionnaires, the whole process for the interviews was transparent and anonymous as well, and all the people involved were informed about the objectives of the LENS project by the interviewer at the beginning of each interview.

During the interviews, two-page physical questionnaires were used by the interviewers where the interviewees were called to answer the same questions that were included in the online surveys (see Figure 2 and 3). The personal data, besides age group and sex, of the interviewees were protected and not documented. Face-to-face interviews did not have the same drawbacks as the online questionnaires. People agreed to take part in this research and readily answered the physical questionnaires.

The results of the analysis of the physical questionnaires combined with the online ones are presented in chapter 4.1, while more detailed information about the responses is given in the Appendix.

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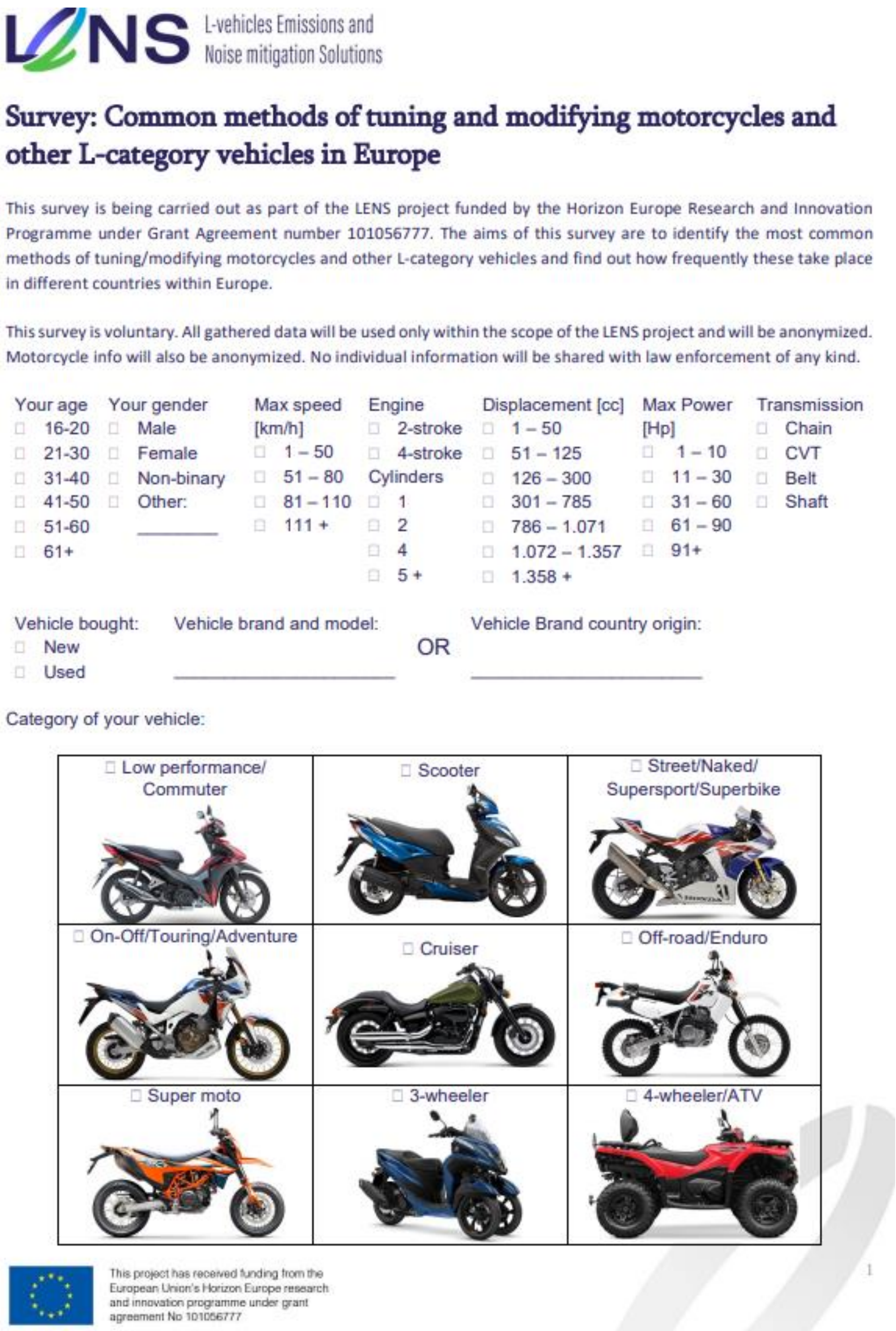

L-vehicles Emissions and Noise mitigation Solutions

Survey: Common methods of tuning and modifying motorcycles and other L-category vehicles in Europe

This survey is being carried out as part of the LENS project funded by the Horizon Europe Research and Innovation Programme under Grant Agreement number 101056777. The aims of this survey are to identify the most common methods of tuning/modifying motorcycles and other L-category vehicles and find out how frequently these take place in different countries within Europe.

This survey is voluntary. All gathered data will be used only within the scope of the LENS project and will be anonymized. Motorcycle info will also be anonymized. No individual information will be shared with law enforcement of any kind.

Your age	Your gender	Max speed [km/h]	Engine	Displacement [cc]	Max Power [Hp]	Transmission
☐ 16-20	☐ Male	☐ 1 – 50	☐ 2-stroke	☐ 1 – 50	☐ 1 – 10	☐ Chain
☐ 21-30	☐ Female	☐ 51 – 80	☐ 4-stroke	☐ 51 – 125	☐ 11 – 30	☐ CVT
☐ 31-40	☐ Non-binary	☐ 81 – 110	Cylinders	☐ 126 – 300	☐ 31 – 60	☐ Belt
☐ 41-50	☐ Other: ________	☐ 111 +	☐ 1	☐ 301 – 785	☐ 61 – 90	☐ Shaft
☐ 51-60			☐ 2	☐ 786 – 1.071	☐ 91+	
☐ 61+			☐ 4	☐ 1.072 – 1.357		
			☐ 5 +	☐ 1.358 +		

Vehicle bought:
- ☐ New
- ☐ Used

Vehicle brand and model: ____________________ OR Vehicle Brand country origin: ____________________

Category of your vehicle:

☐ Low performance/ Commuter	☐ Scooter	☐ Street/Naked/ Supersport/Superbike
☐ On-Off/Touring/Adventure	☐ Cruiser	☐ Off-road/Enduro
☐ Super moto	☐ 3-wheeler	☐ 4-wheeler/ATV

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Figure 2: First page of the physical questionnaires used in the interviews as part of the LENS project.

L-vehicles Emissions and Noise mitigation Solutions

Current mileage of your vehicle: _____________km.
How much do you estimate that you drive the vehicle every year: _______________km.

Vehicle registration year (1st registration):
- ☐ Up to 1998
- ☐ 1999 – 2006
- ☐ 2007 – 2016
- ☐ 2017 – 2020
- ☐ 2021 – 2023

Vehicle usage:
- ☐ Primary means of transport
- ☐ Secondary means of transport
- ☐ Free time
- ☐ Other: _____________

Have you modified or tuned, temporarily or permanently, your vehicle (Excluding regular service, possible repairs, or parts replacement with OEM/original ones)? If so, for what reason? And, who did the modifications?

Categories	List of modifications	Temporary	Reason					Location		
			Power	fuel cons.	Appearance	Sound	Handling	Self	Workshop	Dealer
Exhaust system	☐ Removal of silencer, silencer modifications									
	☐ After-market silencer									
	☐ Catalyst removal									
	☐ Adjustable exhaust valve / db-killer									
	☐ Modifications to exhaust manifold (tubes)									
Air intake	☐ Air filter removal									
	☐ After-market air filter									
Fuel system	☐ After-market fuel injectors									
	☐ After-market carburettor									
ECU and electronics	☐ After-market ECU									
	☐ Software modifications to ECU									
	☐ Engine speed limiter removal									
	☐ After-market spark plugs									
	☐ After-market ignition coils									
Engine	☐ Porting cylinder head									
	☐ After-market camshafts									
	☐ Flywheel weight reduction									
	☐ Increased engine displacement (after-market cylinder, pistons, rods, etc.)									
	☐ Crankshaft weight reduction									
Transmission	☐ After-market final drive gear									
	☐ After-market gearbox gears									
	☐ After-market clutch (slip clutch or regular)									
	☐ Wheelbase increase									
Fairing	☐ Removal of fairing parts									
	☐ After-market fairing									
Other	☐ ________________									

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Figure 3: Second page of the physical questionnaires used in the interviews as part of the LENS project.

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3 Tampering

3.1 Introduction

Tampering refers to any modification by the user that sets a vehicle outside of its type-approved specifications. Examples of tampering are the removal or replacement of the silencer to alter the sound performance of the vehicle or the modification of the ECU to improve its powertrain performance. Common tampering methods are analyzed further in chapter 3.2. However, these changes often take place without considering any possible negative impact on the noise and emission levels. As various studies show, tampering may lead to significantly negative effects, affecting not only the environment, but human health as well [9, 17, 18, 19].

Zardini et al. [2] showed that tampered vehicles with modifications that aimed to improve the vehicle's performance can result to detrimental effects on both regulated and unregulated exhaust emissions, and, consequently, pose a serious threat to air quality.

As Hernandez et al. [3] argue, pollutant and noise emissions from LVs, and especially from motorcycles, can have harmful effects on both the environment and human health. These effects seem to be the result of historically more relaxed emission standards than other vehicle categories and peak noise levels that are higher than those of other types of vehicles. Hence, despite their low seating capacity, LVs are one of the biggest contributors to noise from road transport. More specifically, at high speeds, the sound produced by motorcycles can be perceived as almost twice that of cars [3], which equals to a 10 dB difference [10].

Giechaskiel et al. [4] confirm that such illegal modifications pose a severe problem not only regarding LVs, but Heavy-Duty Vehicles and Non-Road Mobile Machinery as well. Even the latest generation vehicles can be tampered, thus almost completely cancelling their advanced systems' benefits, and leading to serious environmental and health consequences.

Dittrich et al. [20] have found numerous roadside sound levels of LVs in urban streets of 90-100 dB(A) and higher, and the sound characteristics that are particularly disturbing for nearby residents. The combination of fast acceleration, engine revving, high engine speeds, strongly fluctuating noise and low frequency engine noise are a particular cause of annoyance and sleep disturbance leading to health impacts including stress, headaches, fatigue and even heart disease in the long term. Other impacts include concentration loss, quality of life loss and living space restriction due to closing windows to shut out noise. High noise levels and low frequencies are insufficiently blocked by normal windows. Many of the loud LVs identified seem to be tampered and/or driven aggressively. The sound signature of loud vehicles contains features that can be linked to tampering, such as strong tonal frequency peaks and backfire sounds.

The wide availability of vehicle tuning and components is partly the cause of this situation, whether done by vehicle owners or by workshops. Vehicle tuning is widely on offer on the internet, as can easily be confirmed by searching for vehicle make + tuning. Both mechanical tuning parts and ECU flash services products are on offer.

It is therefore evident that tampering poses a severe problem that contributes to the deterioration of air and noise pollution. However, the actual magnitude of the current situation regarding tampering in the EU is yet to be quantified. The fact that some modifications may be hard to detect, either because they are adjustable or easy to remove and reapply after inspection, makes this work even more difficult. Hence, it is imperative to take anti-tampering measures with a view to preventing such modifications and decreasing

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these detrimental effects. Such measures could include guides or manuals [19] that will contribute to identifying tampered vehicles easier.

3.2 Methods

There are numerous ways to tamper a vehicle. The modifications may target different systems of the vehicle: the exhaust (mainly muffler or catalyst), the air intake, the fuel system, the ECU and electronics, the engine, the transmission, or even the vehicle chassis including the fairing. These are the categories examined in the present study. Figure 4 indicates common LV tampering methods targeting some of these systems.

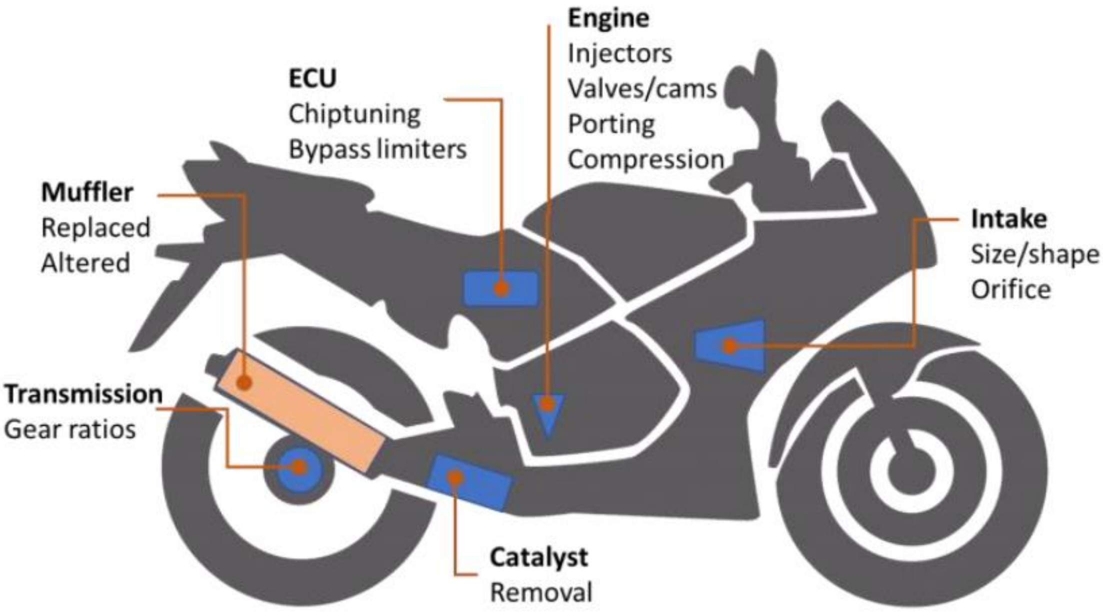

Figure 4: Common tampering methods applied in LVs.

More specifically, the most common tampering methods by each category include the following:

- Exhaust:
    - After-market silencer: the work principle of a silencer is to reduce noise emission by cross-section variations causing internal sound reflection, and/or dissipation of sound by means of absorptive material inside the silencer. Replacement of the OEM silencer by an after-market one which is not certified for the vehicle or had an incorrect certification [21], can lead to higher noise levels.
    - Removal of silencer, silencer modifications: removing the silencer inevitably leads to a strong increase in noise. If the catalyst forms part of the silencer of a vehicle, then the removal of the silencer is equal to the removal of the catalyst and an increase in pollutant emissions will be observed.

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    - Catalyst removal: the catalyst works as a filter that converts harmful exhaust emissions to ones of less significance and thus the removal of it results in a remarkable increase in pollutant emissions. It is often removed to deliver the exhaust unrestricted to the environment.
    - Modifications to the exhaust manifold (tubes): such modifications allow exhaust gases to flow more freely and thus, higher power and torque can be achieved.
    - Adjustable exhaust valve/dB killer: by having an adjustable exhaust valve, one can adjust the sound levels of the vehicle. The valve can be either open or closed. The former allows the vehicle to emit higher noise levels. A dB killer is easily removed by the owner, resulting in much higher noise levels.
- Air intake:
    - After-market air filter: an air filter works by filtering the air in the intake, before entering the engine, in order to improve the air flow and fuel consumption.
    - Air filter removal: by removing the air filter of a vehicle, the intake air flow is increased, and better combustion can be achieved. The sound levels of the vehicle may also be affected.
- Fuel system:
    - After-market carburettor: the carburettor is responsible for controlling and mixing the air and fuel that enters the engine.
    - After-market fuel injectors: the fuel injectors control the injection of the fuel into the engine.
- ECU and electronics:
    - Software modifications to the ECU: the ECU consists of both hardware and software parts, and it affects numerous systems of the vehicle. The modifications that can be done vary.
    - After-market ECU: the replacement of the ECU with an after-market one is likely aiming to achieve a richer combustion and therefore more power.
    - After-market spark plugs: spark plugs use the high voltage electricity produced by the ignition coils to ignite the air/fuel mixture and start the combustion.
    - After-market ignition coils: ignition coils are used to transform the battery voltage to much higher voltages that are required for the operation of the spark plugs.
    - Engine speed limiter removal: once the speed limit is met, the flow of air and fuel to the engine is restricted so as to not exceed the said limit. In some engines, for example mopeds, the mechanical speed limiter can be removed easily using commercially available parts.
- Engine:
    - Porting cylinder head: the modification of the cylinder head refers to the modification of the intake and exhaust ports of the engine with a view to improving the air flow.
    - After-market camshafts: the camshafts are responsible for opening and closing the inlet and outlet valves of the combustion chamber.

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    - Increased engine displacement (after-market cylinder, pistons, rods, etc.): the objective of increasing an engine's displacement is to increase both power and speed of the vehicle by allowing more air into the engine.
    - Flywheel weight reduction: a flywheel is a heavy wheel whose main function is to store kinetic energy for keeping the engine at a constant speed.
    - Crankshaft weight reduction: the crankshaft converts the linear motion, which is the result of the combustion in the engine, to rotational motion.
- Transmission:
    - After-market final drive gear: the final drive gear connects the power generated by the internal combustion engine to the rear wheel for the vehicle to be moved.
    - After-market clutch (slip clutch or regular): the basic functions of a clutch are to either change the speed of the vehicle or make it stop.
    - After-market gearbox gears: device that changes the speed or direction of rotation by using gears.
    - Wheelbase increase: the wheelbase refers to the distance between the front and rear wheels of a vehicle.
- Fairing:
    - After-market fairing: fairing refers to aerodynamically designed parts that surround the vehicle in order to protect both the vehicle's engine and the rider. Their replacement with after-market ones is usually done for aesthetic reasons.
    - Removal of fairing parts: since the original parts are designed to achieve optimum drag coefficient, by removing them the air resistance of the vehicle is modified and thus, the fuel consumption may increase.

The effects that the above-mentioned types of tampering may have on both pollutant and noise emission levels are further analyzed in chapter 4.2.

Note that, in the scope of this study, after-market parts refer to both certified and non-certified parts that can be applied to vehicles and are not manufactured by OEMs.

The reasons that lead to the implementation of these modifications differ. The most common ones comprise the power increase, better fuel economy, sound performance, individualized appearance and performance, or handling, or a combination of several of these reasons. Other reasons may include the avoidance of maintenance costs, or the fact that after-market parts may cost less than OEM ones. Whatever the reason, after-market non-OEM parts may not meet specific standards that must be met by the vehicles by legislation and their use may therefore contribute to the deterioration of the pollutant and noise emission performance of the vehicles. Finally, the wide availability of tuning services and vehicle parts facilitate tampering, which in turn is driven by demand and example.

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4 Results

4.1 Questionnaire results

The survey that was conducted consisted of both online questionnaires and face-to-face interviews, during which the interviewees were asked to answer the same questions that were included in the online questionnaires. In total, 666 questionnaires were completed. The online ones were completed in more than 20 EU countries, while the interviews were conducted only in Greece. Even though the questionnaires were specifically targeting people that had modified their vehicles at least once, there were still some cases – 160 to be exact – in which no modifications were mentioned. These questionnaires were not taken into consideration and therefore, only 506 questionnaires were reviewed further (see Table 1). The results that follow, shown in Figures 5 to 20 and Tables 1 to 6, include data from only the valid questionnaires. It is also worth mentioning that in some cases, participants referred to some non-significant modifications, such as applying stickers or a different license plate holder to the vehicle, as tampering attempts. These were also not included in the analysis. More detailed information about the questionnaire responses is given in the Appendix. After processing and reviewing the results of both the online questionnaires and in-person interviews, the following could be concluded:

Table 1: Total number of questionnaires.

	Online Questionnaires	Face-to-face interviews	Total
Questionnaires completed	602	64	666
No modifications mentioned	157	3	160
Reviewed Questionnaires	445	61	506

As shown in Figure 5, over 20 European countries participated in the survey, with Austria being in the lead, followed by Greece, Germany, and Italy. The majority (84%) of the participants were between 20-50 years old, while the age group 31-40 was the most common one. Almost all (96%) of the participants were males (see Figure 6).

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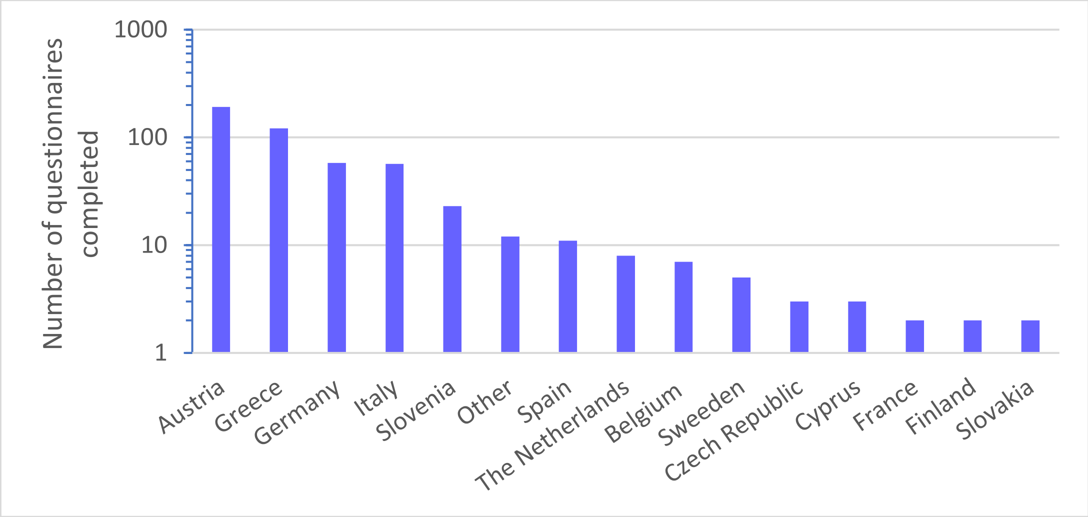

Figure 5: Number of questionnaires per country (y-axis is logarithmic).

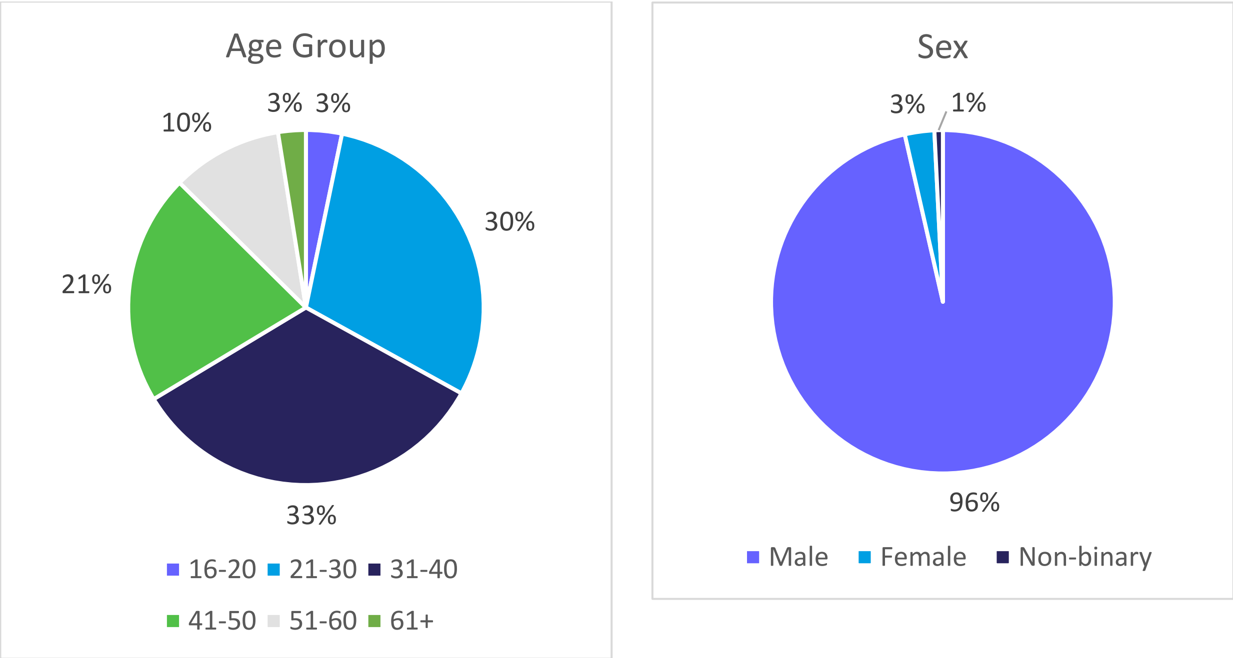

Figure 6: Questionnaire results regarding participants' age group and sex.

As Figure 7 indicates, most vehicles (76%) were registered after 2007. The majority of them (35%) were registered between 2007 and 2016. There was still a quite large percentage (10%) of vehicles that were registered up to 1998, but also a 20% that was registered after 2021. Almost half of the vehicles (48%) belonged to the category Street/Naked/Supersport/Superbike, followed by On-Off/Touring/Adventure (23%) and Super moto (11%). The remaining 18% corresponds to the other LV categories.
Most people mentioned that they most frequently use their vehicle either in their free time (67%) or as a secondary means of transport (17%). Only 12% of the participants use the vehicle as a primary means of transport.

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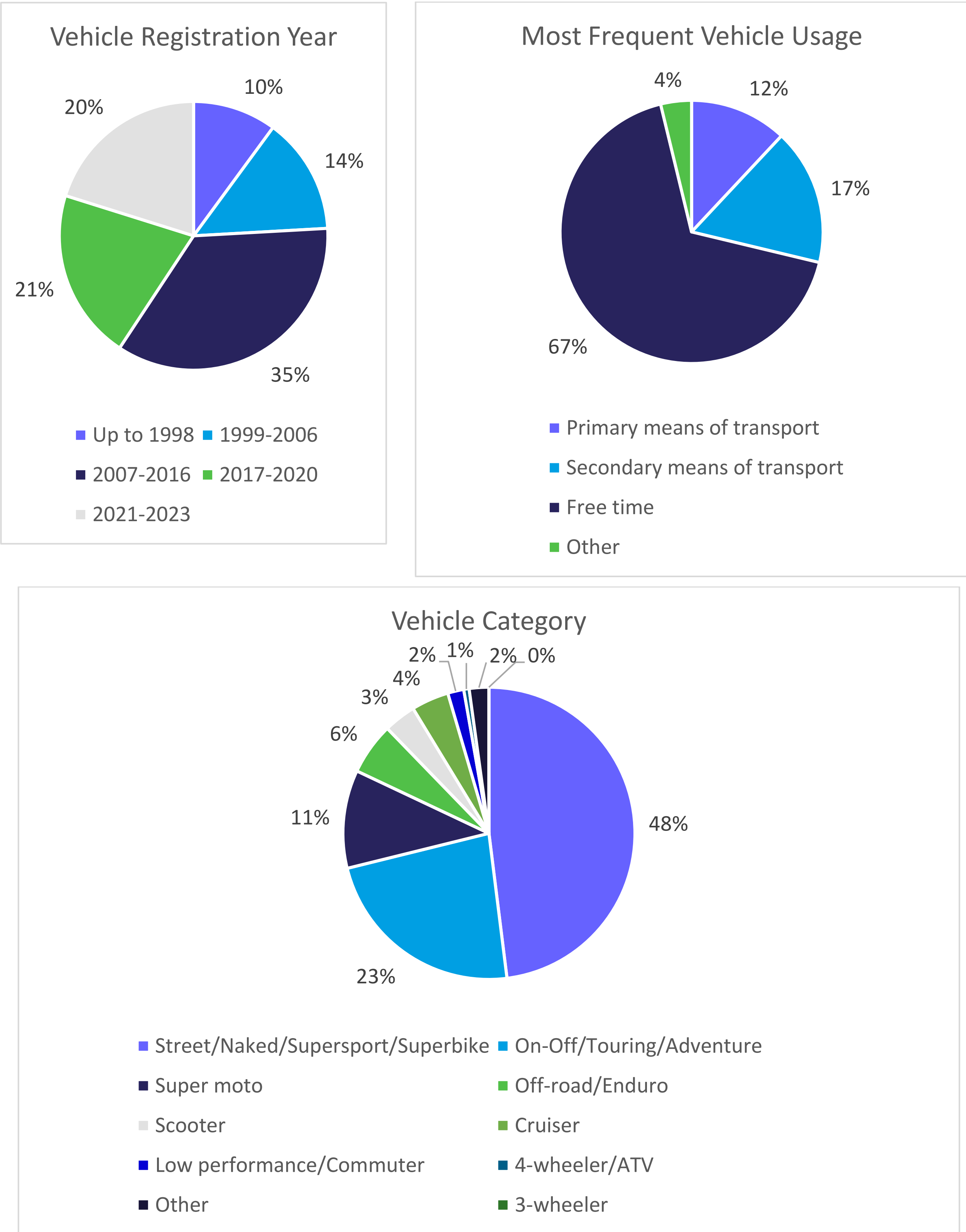

Figure 7: Questionnaire results regarding vehicles' registration year, category, and most frequent usage.

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As shown in Figure 8, 66% of the participants owned a second-hand LV, opposed to 34% of them that bought it brand new. Almost all vehicles (95%) could reach a maximum speed of more than 111 km/h and had a 4-stroke engine. The transmission of most of them (87%) was of chain type. Half of the vehicles (51%) (see Figure 9) had 2 cylinders, while the engine displacement of the majority of them (90%) was between 301-1,357 cc. More specifically, 33% was between 786-1,071 cc, 32% between 301-785 cc and 25% between 1,072-1,357 cc. The maximum power of more than half of the vehicles (56%) exceeded 91 Hp, while that of 25% of them was between 61-90 Hp and of 12% of them between 31-60 Hp.

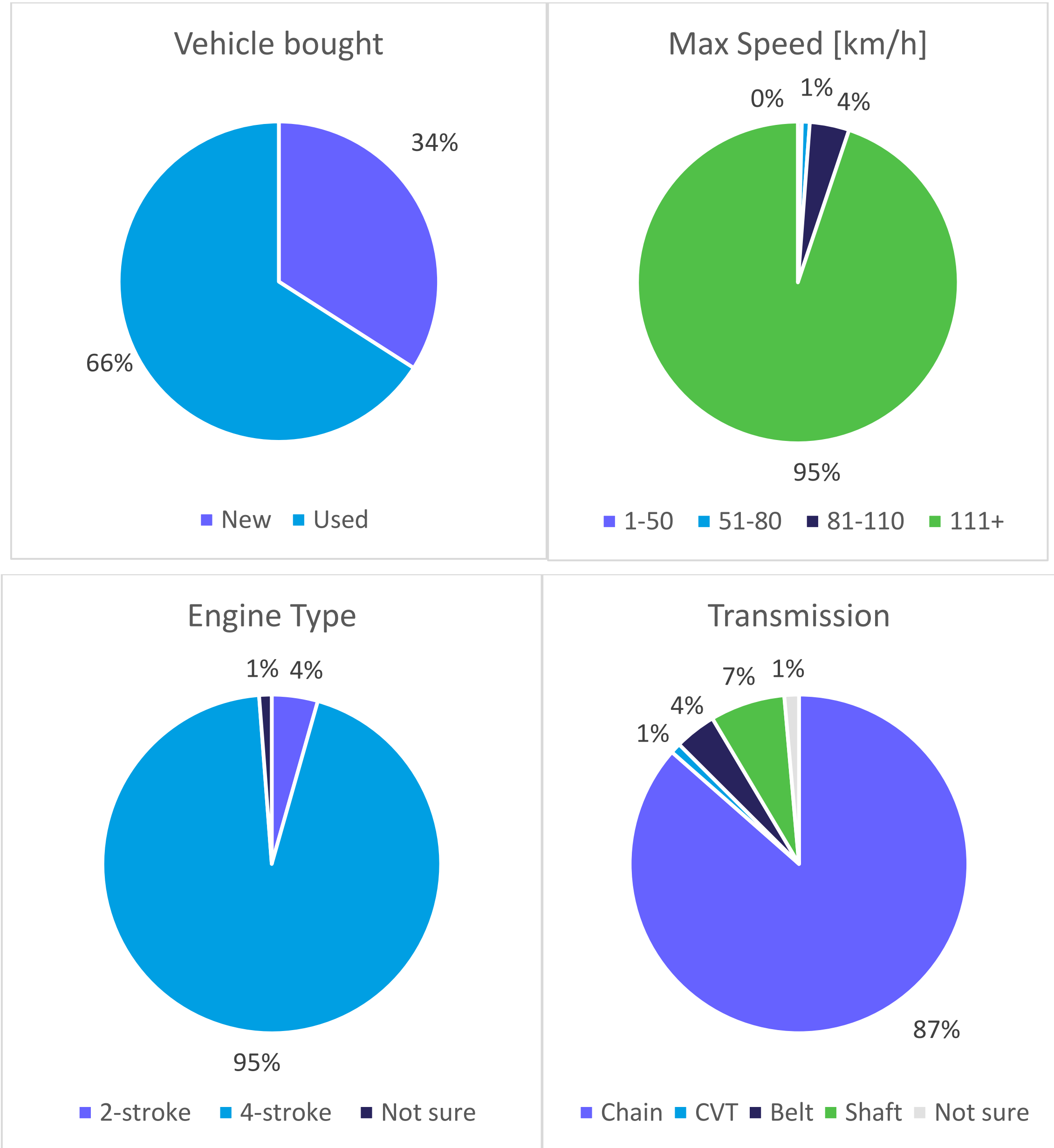

Figure 8: Questionnaire results regarding vehicle type, maximum speed, engine and transmission type.

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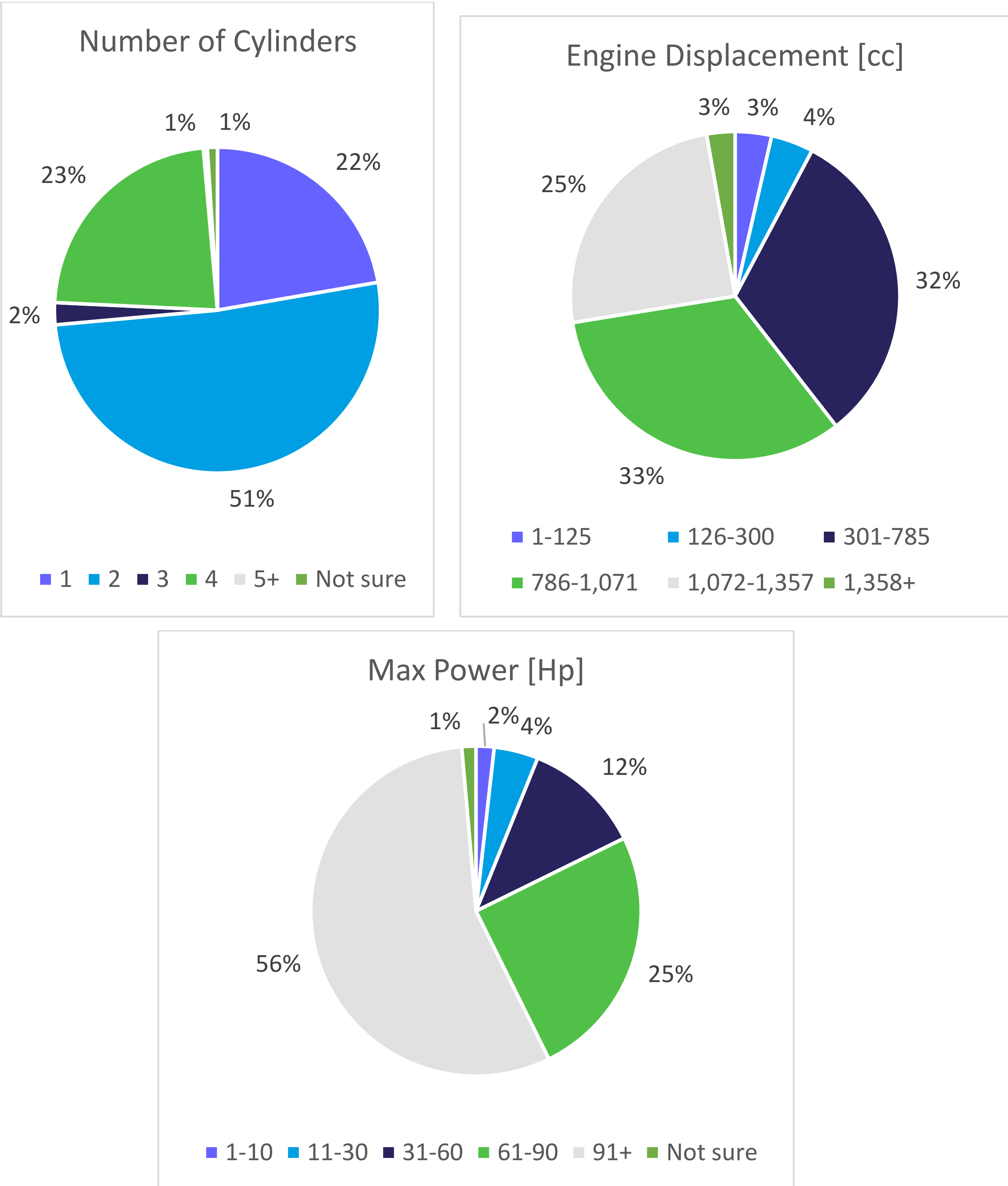

Figure 9: Questionnaire results regarding the number of cylinders, engine displacement, and maximum power.

The most popular modification turned out to be the after-market silencer, as more than half of the participants (325) stated having applied one in their vehicle (see Figure 10). Next in the ranking was the after-market air filter, followed by after-market fairing and software modifications to the ECU. The least popular modification, on the other hand, was the shifter and wheelbase increase. The ranking of the 25 most common tampering modifications included in the questionnaires is shown in Table 2 as well.

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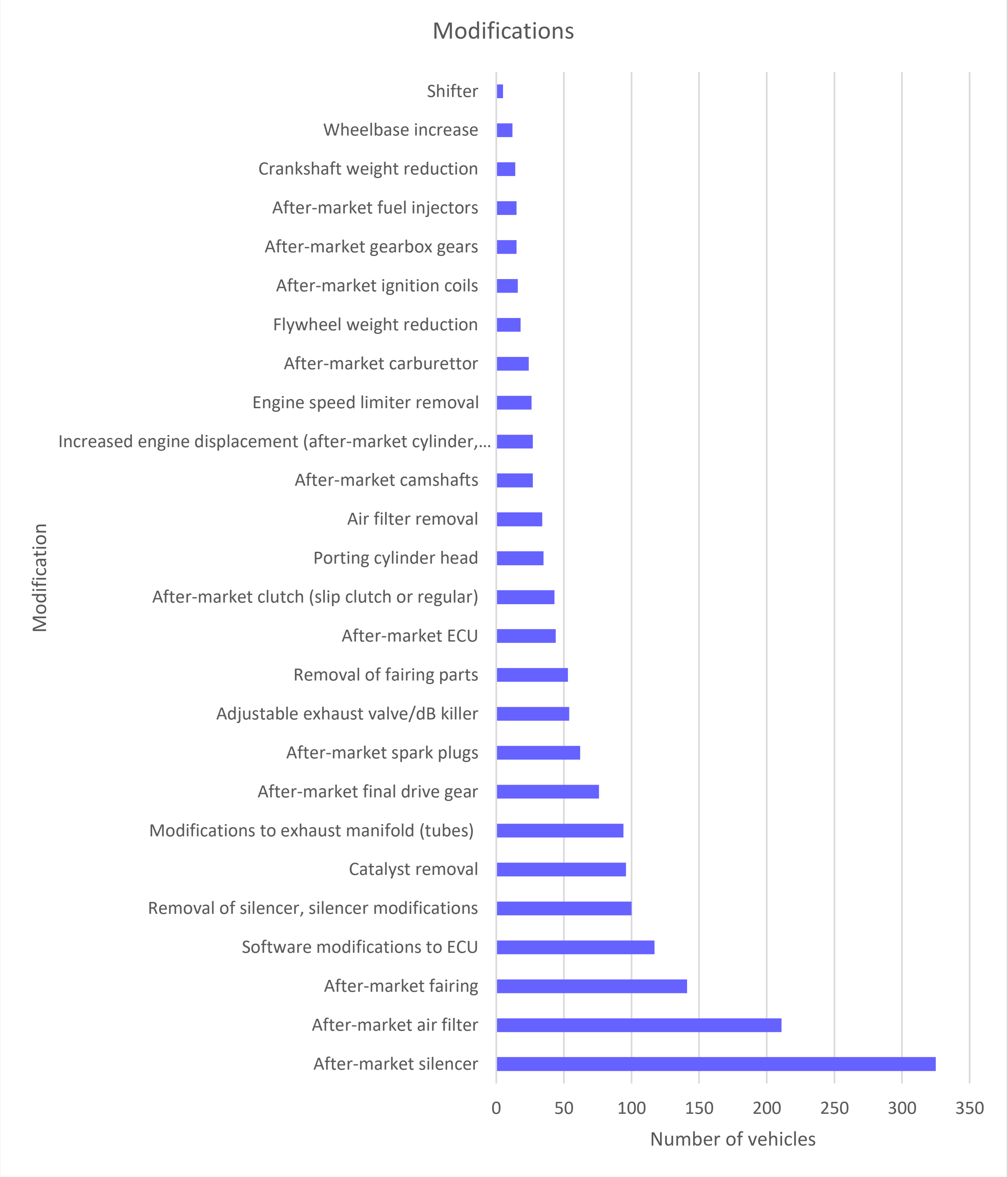

Figure 10: Number of vehicles that have implemented each modification.

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Table 2: Ranking of most common tampering methods.

No. Ranking	Category	Modification
1	Exhaust	After-market silencer
2	Air Intake	After-market air filter
3	Fairing	After-market fairing
4	ECU and electronics	Software modifications to ECU
5	Exhaust	Removal of silencer, silencer modifications
6	Exhaust	Catalyst removal
7	Exhaust	Modifications to exhaust manifold (tubes)
8	Transmission	After-market final drive gear
9	ECU and electronics	After-market spark plugs
10	Exhaust	Adjustable exhaust valve/dB killer
11	Fairing	Removal of fairing parts
12	ECU and electronics	After-market ECU
13	Transmission	After-market clutch (slip clutch or regular)
14	Engine	Porting cylinder head
15	Air Intake	Air filter removal
16	Engine	After-market camshafts
17	Engine	Increased engine displacement (after-market cylinder, pistons, rods, etc.)
18	ECU and electronics	Engine speed limiter removal
19	Fuel System	After-market carburettor
20	Engine	Flywheel weight reduction
21	ECU and electronics	After-market ignition coils
22	Transmission	After-market gearbox gears
23	Fuel System	After-market fuel injectors
24	Engine	Crankshaft weight reduction
25	Transmission	Wheelbase increase

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As shown in Figure 11, while 46% of the participants responded that they had made 1 or 2 modifications to their vehicle, there was still a significant number of people (19%) that admitted having modified their vehicle in more than 6 different ways. Figures 12 to 14 also present how the category of the vehicle, the most frequent vehicle usage, and the age group of the vehicle's owner may influence the number of modifications, both by total number of vehicles and as percentages.

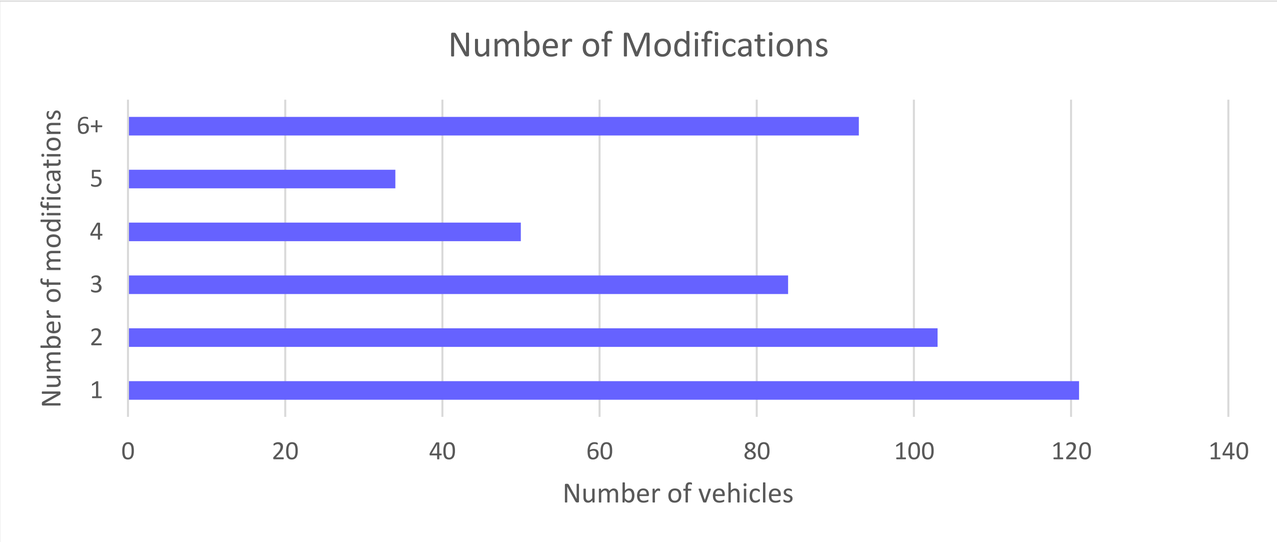

Figure 11: Number of modifications implemented by number of vehicles.

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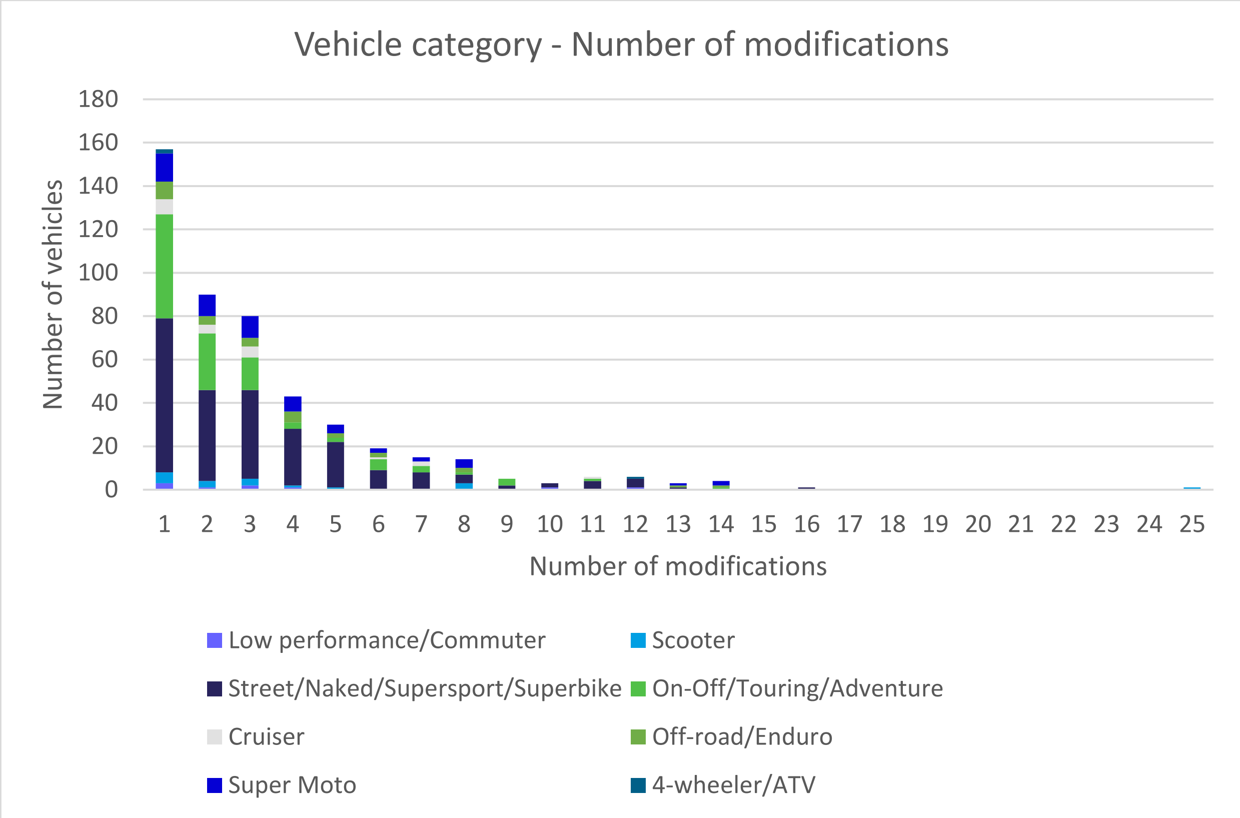

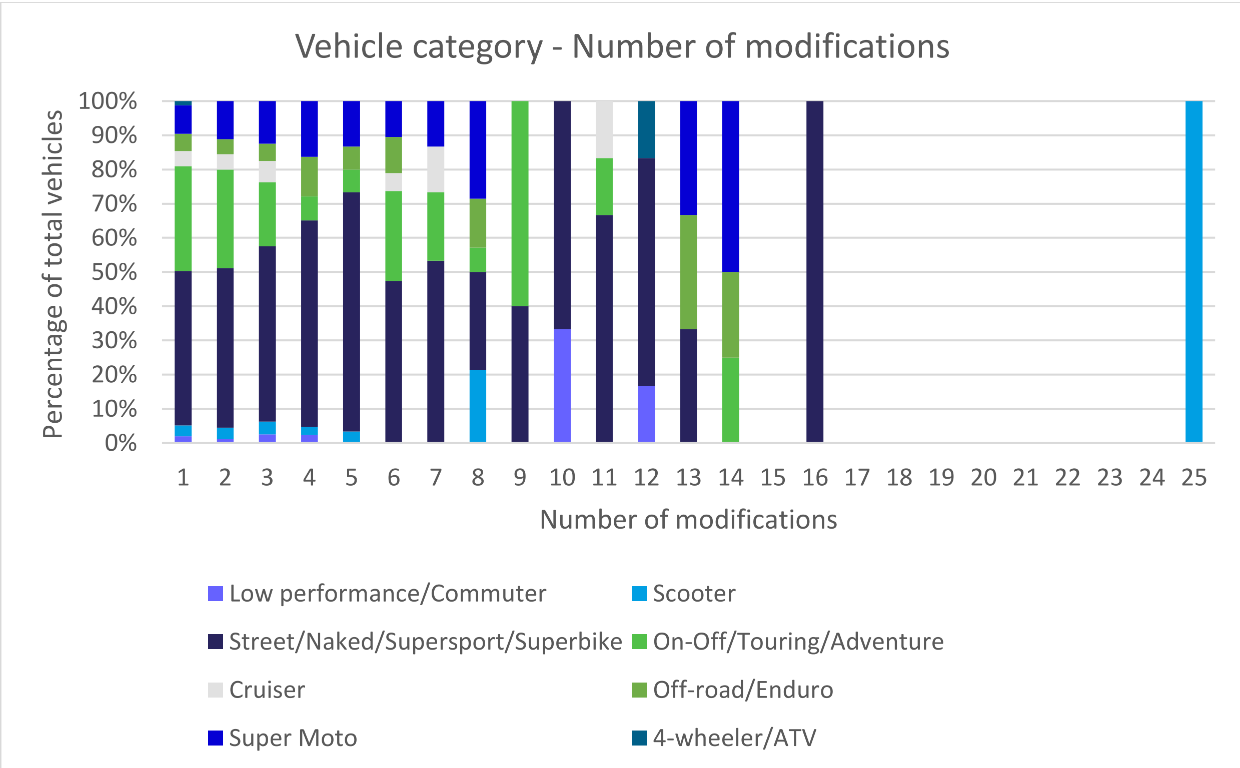

Figure 12: Influence of vehicle category to the number of modifications (top: by total number of vehicles, bottom: as a percentage).

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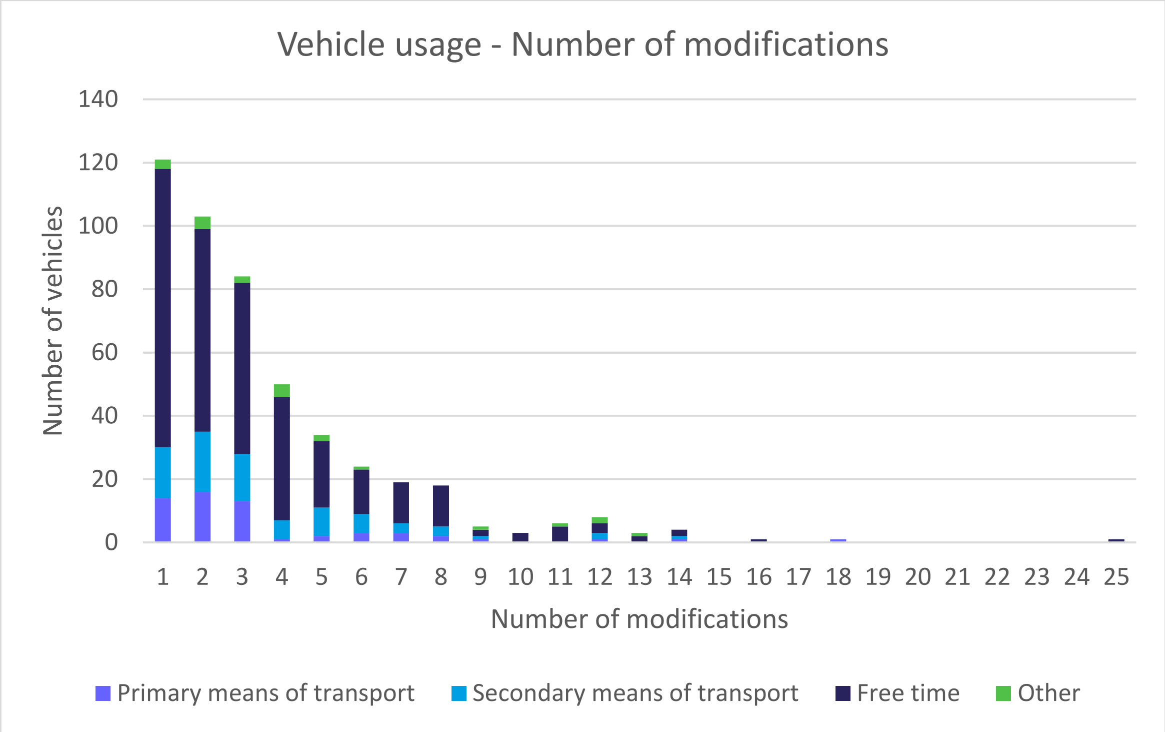

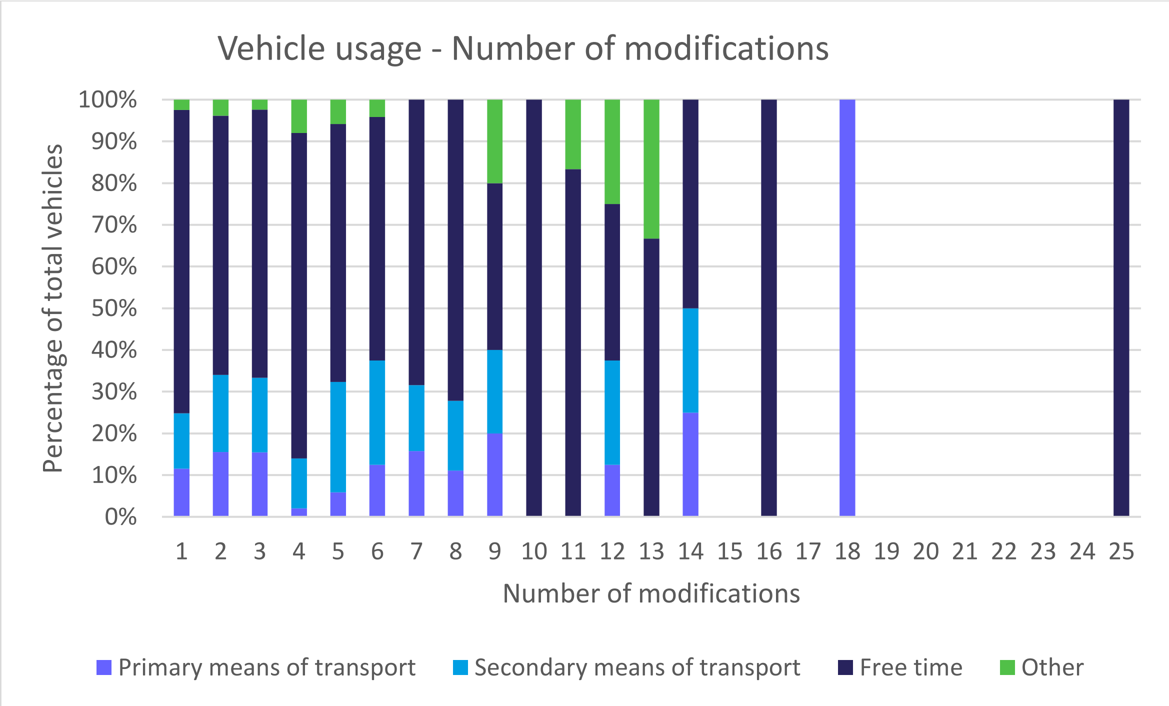

Figure 13: Influence of vehicle usage to the number of modifications (top: by total number of vehicles, bottom: as a percentage).

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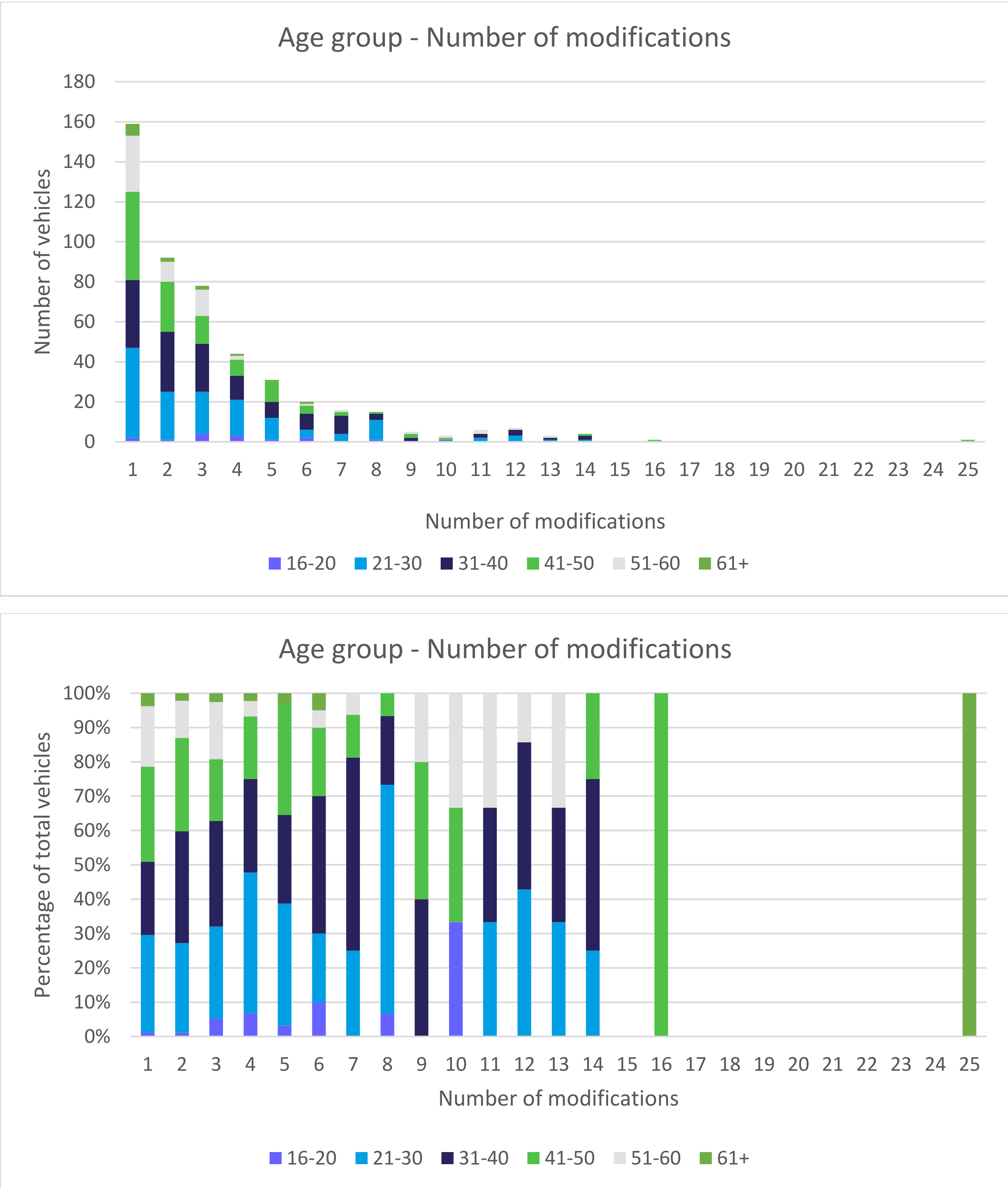

Figure 14: Influence of age group to the number of modifications (top: by total number of vehicles, bottom: as a percentage).

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Figures 15 and 16 present the number of vehicles that have implemented each modification, by modification category. The most popular modification by category was:

- Exhaust: after-market silencer
- Air intake: after-marker air filter
- Fuel system: after-market carburettor
- ECU and electronics: software modifications to the ECU
- Engine: porting cylinder head
- Transmission: after-market final drive gear
- Fairing: after-market fairing

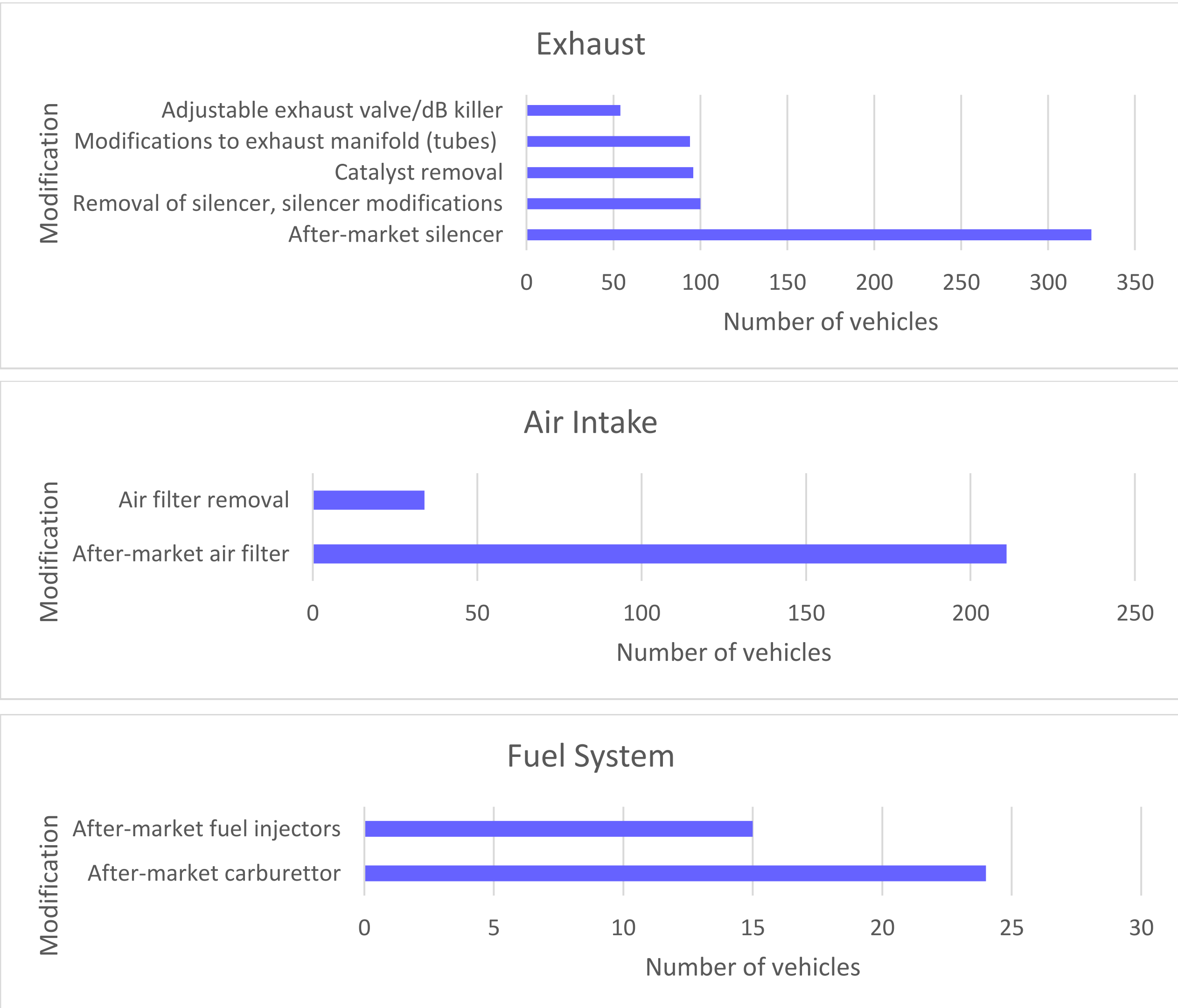

Figure 15: Number of vehicles that have implemented each modification by category: exhaust, air intake, and fuel system.

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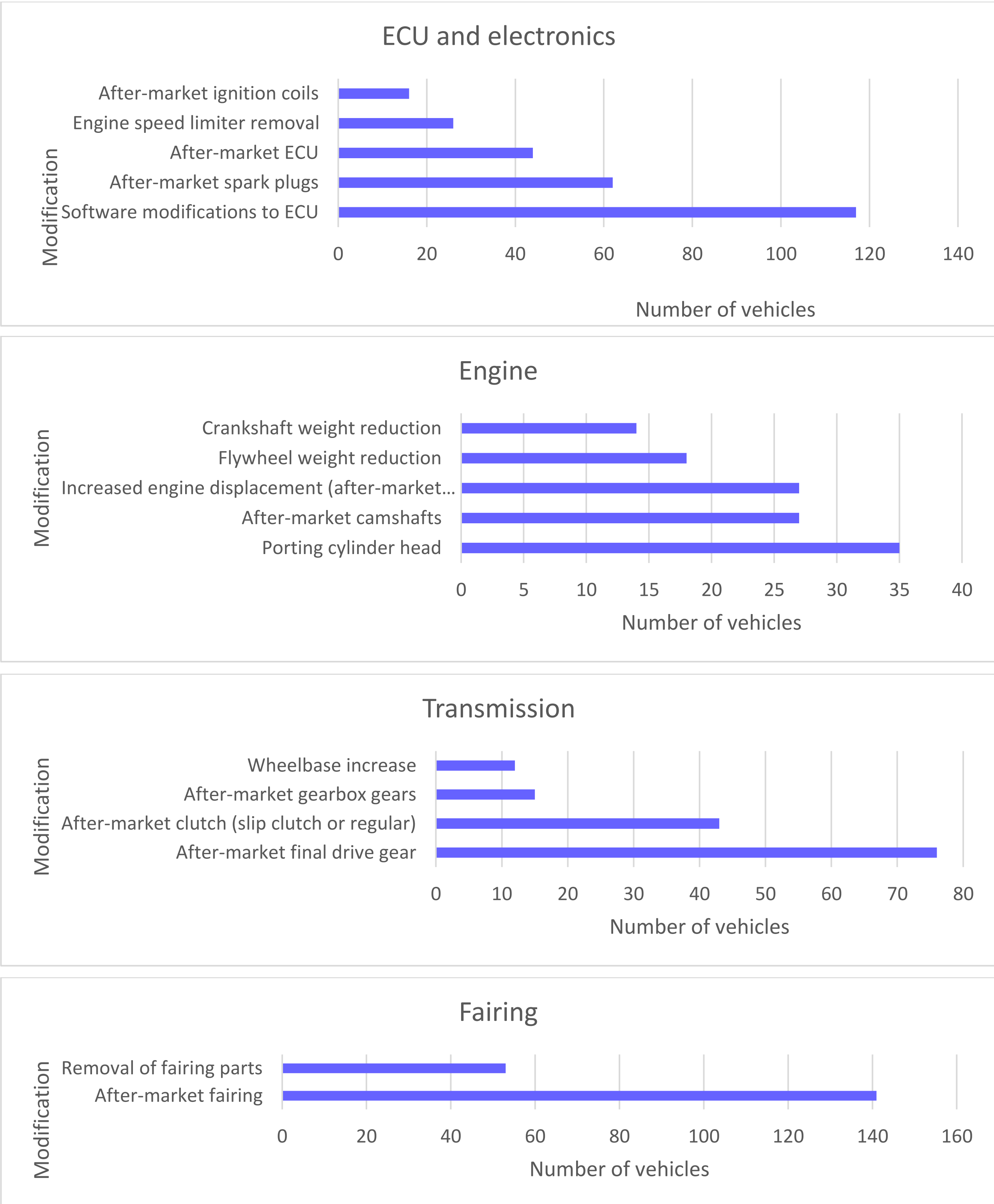

Figure 16: Number of vehicles that have implemented each modification by category: ECU and electronics, engine, transmission, and fairing.

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As Figure 17 indicates, most modifications were targeting the exhaust system (36%), the ECU and electronics (16%) and the air intake system (14%). LV tampering is most frequently (47%) motivated by the need to increase engine power, while 21% of the participants admitted that they have tampered their LV to increase noise and 13% for aesthetic reasons. Table 3 presents the ranking of the five most common reasons behind modifications by each modification category. For all categories, the main reason behind the modifications was the achievement of more power, except the exhaust category, in which the modifications were aiming for the vehicle to produce better sound, and the fairing category, the modifications in which are mostly made for better appearance.

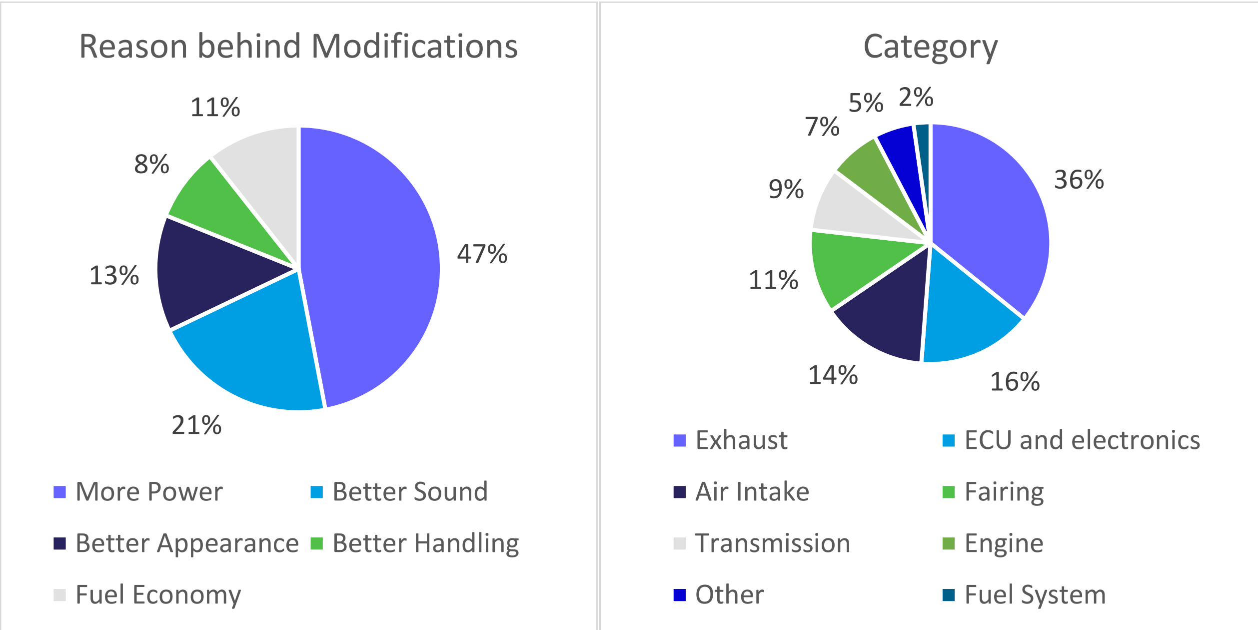

Figure 17: Questionnaire results regarding reasons behind modifications and modification category.

Table 3: Ranking of reasons behind modifications by modification category.

Reason behind Modifications	Category						
	Exhaust	Air Intake	Fuel System	ECU and electronics	Engine	Transmission	Fairing
More Power	2	1	1	1	1	1	3
Better Sound	1	3	3	5	5	5	4
Better Fuel Economy	5	2	2	2	2	4	5
Better Appearance	3	4	5	4	4	3	1
Better Handling	4	5	4	3	3	2	2

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More than half of the participants (59%) admitted to having done the modifications themselves, while 29% had done them at a workshop. Most of them (69%) have made permanent modifications and the remaining 31% have made temporary ones (see Figure 18). Table 4 shows the most common answer to these two questions by each modification category. Across all categories, the majority of modifications were permanent and were done by the owners, except of the majority (46%) of modifications in the ECU and electronics category, which were done in workshops.

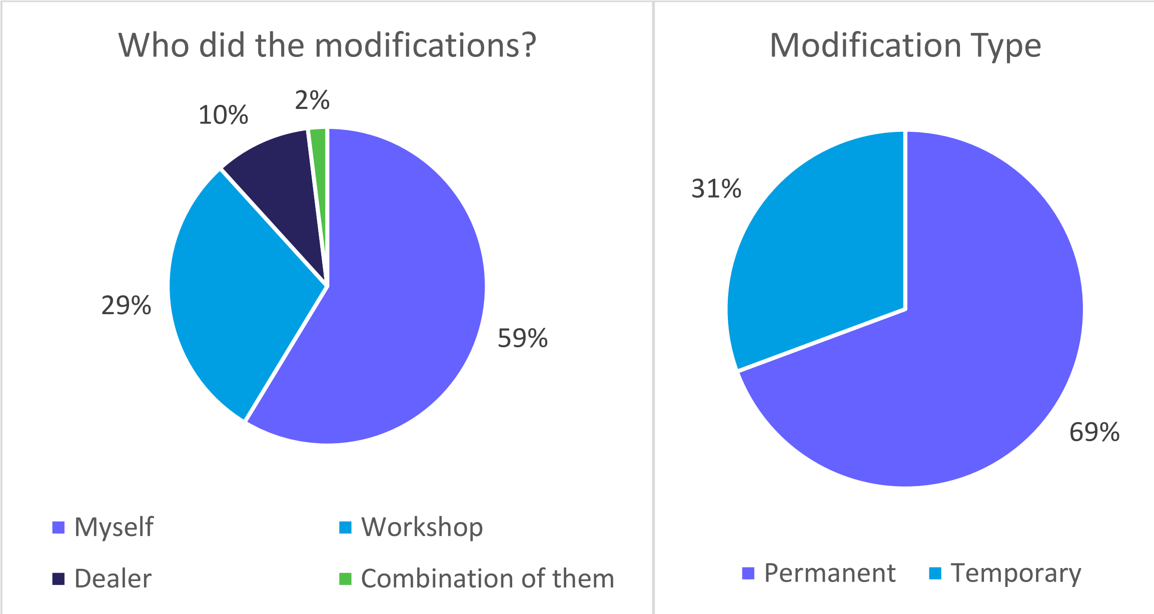

Figure 18: Questionnaire results regarding the person that implemented the modifications and the modification type.

Table 4: Most common answer by modification category.

Question	Category					
	Exhaust	Air Intake	ECU and electronics	Engine	Transmission	Fairing
Who did the modifications?	Myself (57%)	Myself (63%)	Workshop (46%)	Myself (53%)	Myself (60%)	Myself (81%)
Modification Type	Permanent (70%)	Permanent (68%)	Permanent (66%)	Permanent (82%)	Permanent (71%)	Permanent (63%)

The annual distance travelled by the vehicles is shown in Figure 19, as estimated by the participants. Based on these distances, the total estimated annual distance travelled by the total number of vehicles that had each modification was also calculated (see Figure 20). In this way, it could be estimated which modifications have the biggest impact on pollutant and noise emissions, since the biggest the distance travelled, the bigger share of the total amount of emissions. The results indicate the same order as the total number of

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vehicles (see Figure 10), meaning that the modification with the biggest effect was the after-market silencer and the less significant one was the wheelbase increase.

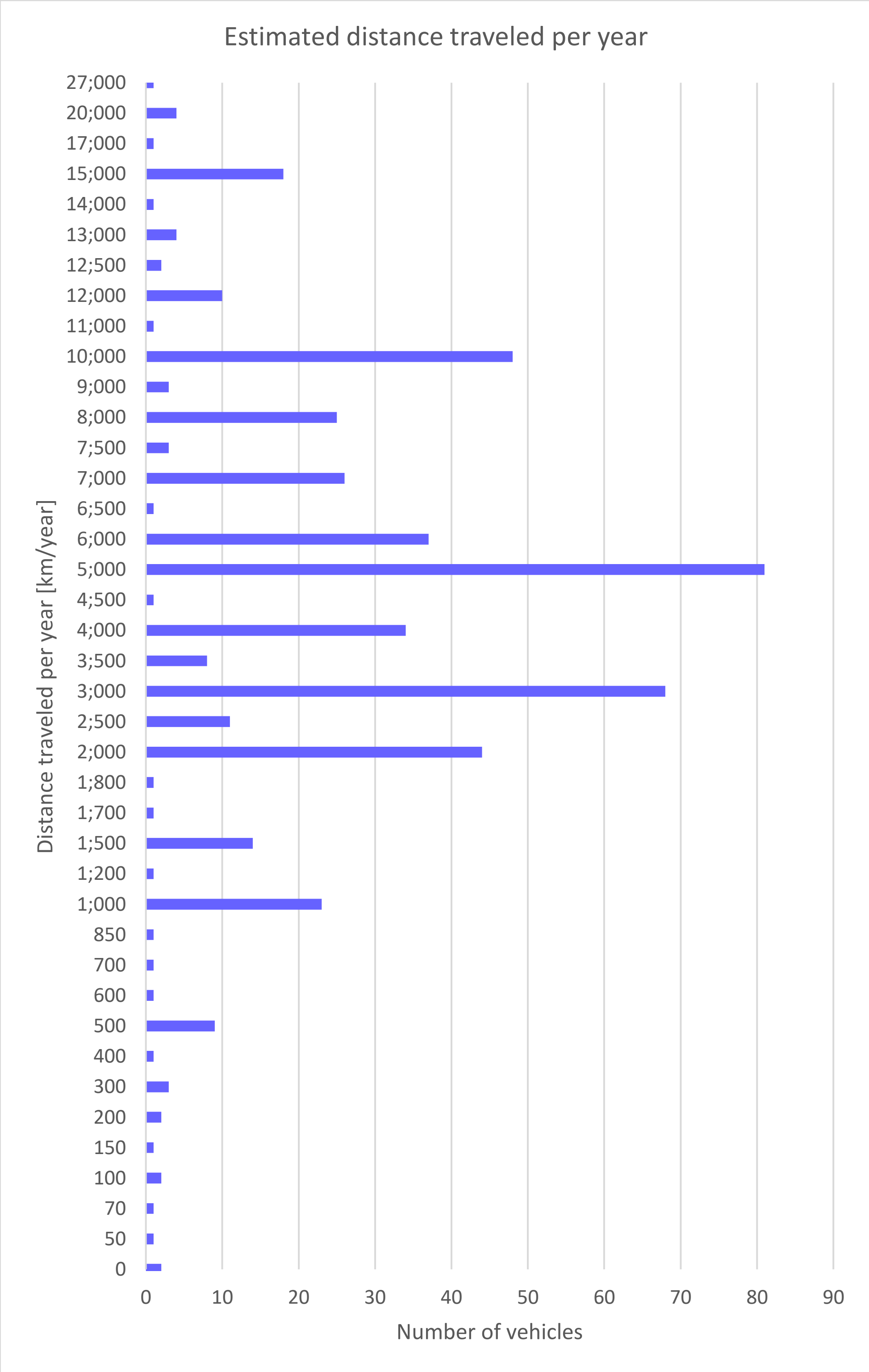

Figure 19: Estimated distance travelled per year by number of vehicles.

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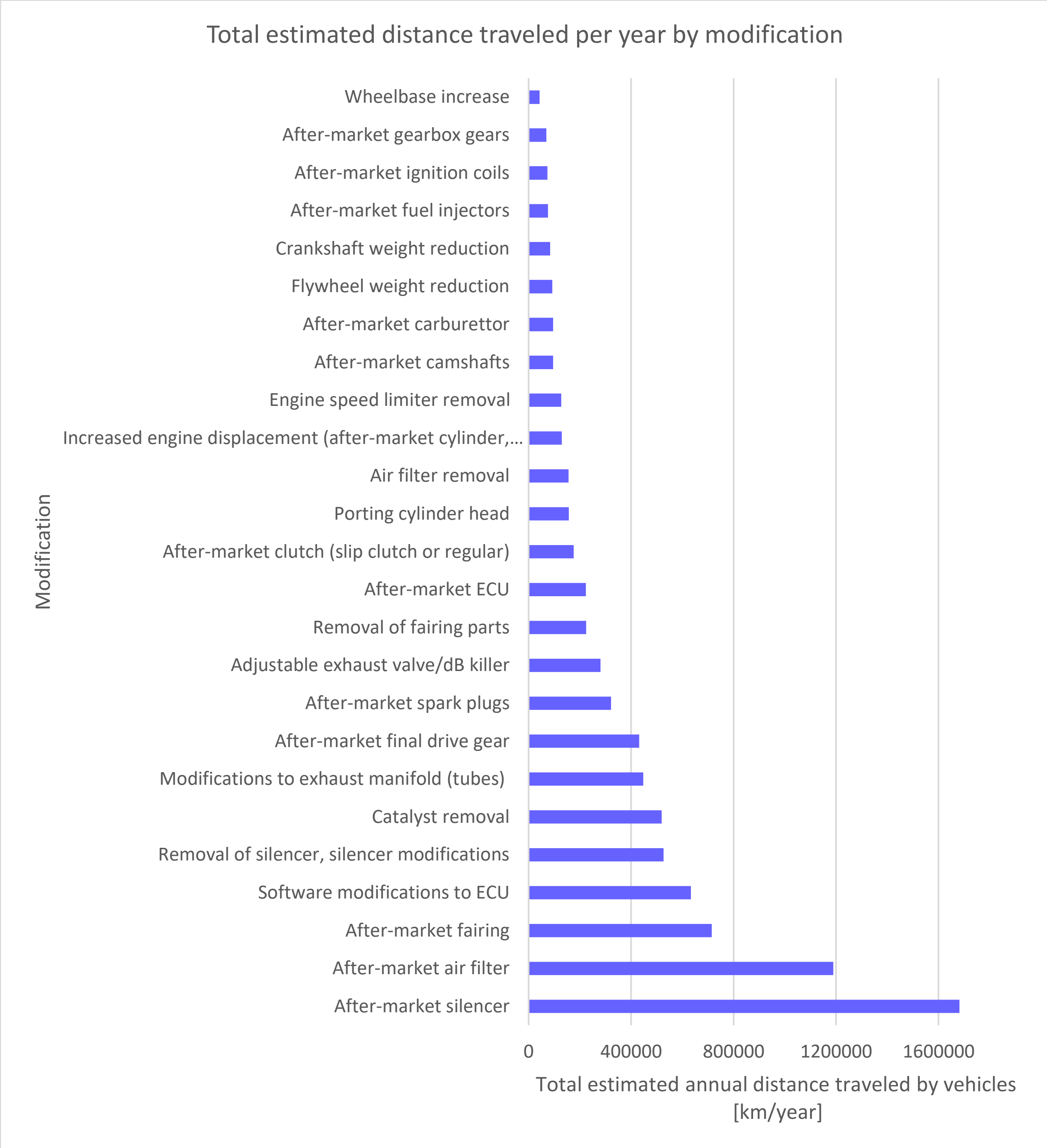

Figure 20: Total estimated distance travelled per year by modification.

Figures 21 and 22 show the influence that the vehicle category and the most frequent use of the vehicle may have on the annual distance travelled by it, both by total number of vehicles and as a percentage.

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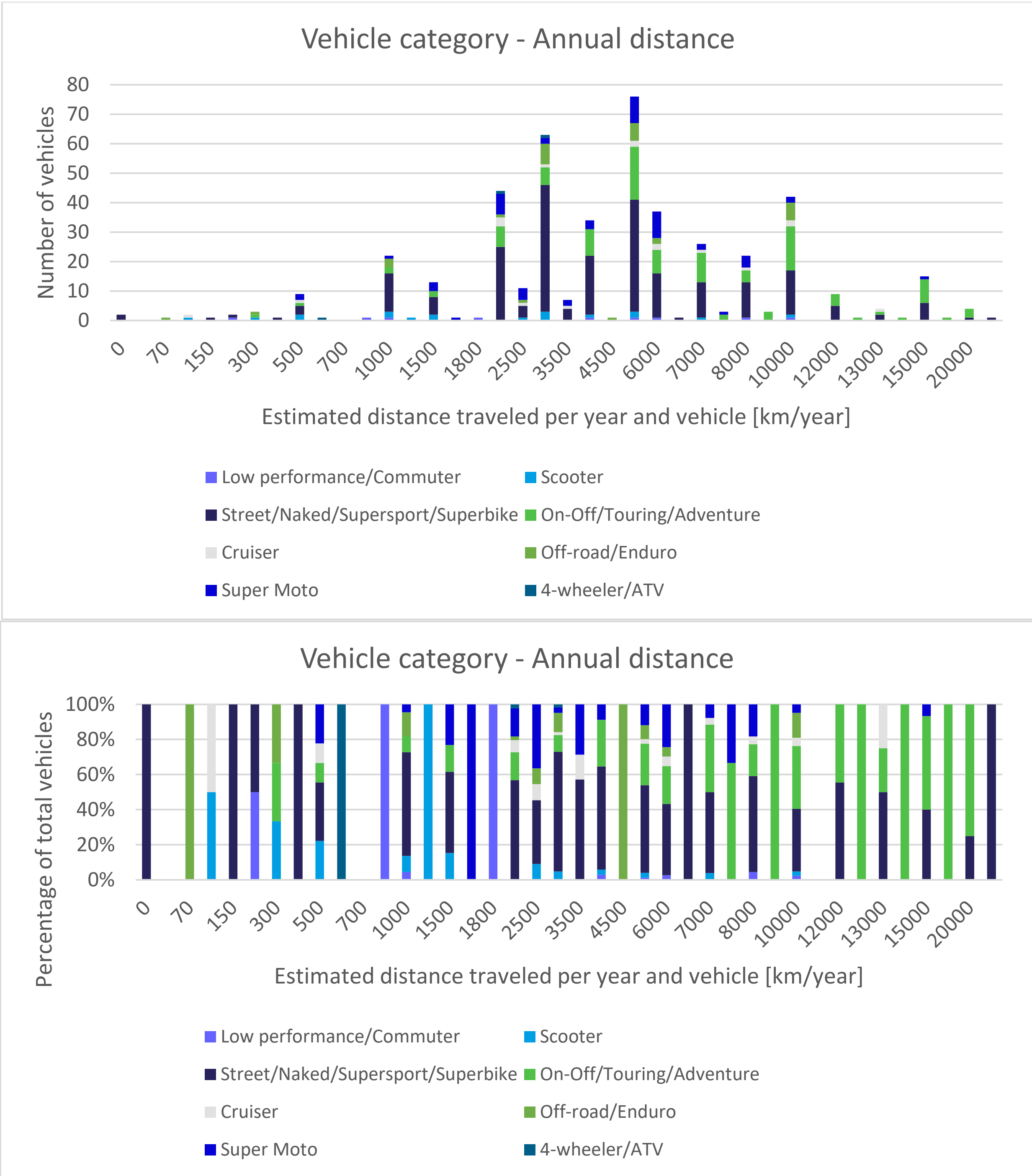

Figure 21: Influence of vehicle category to the number of modifications (top: by total number of vehicles, bottom: as a percentage).

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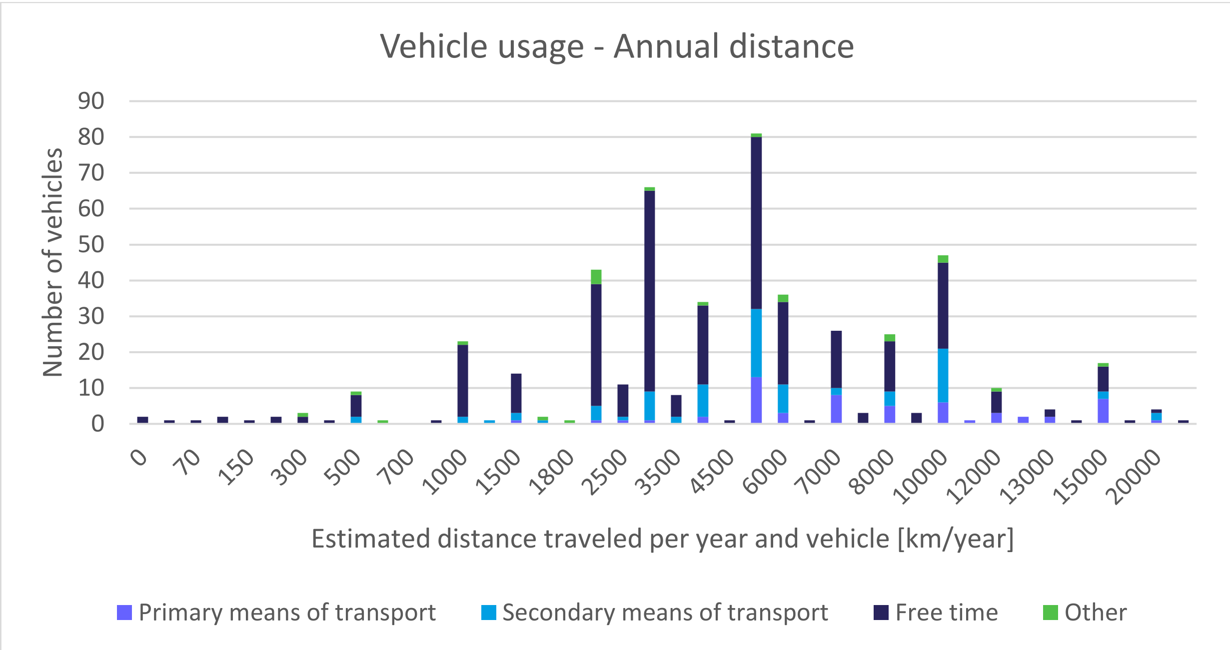

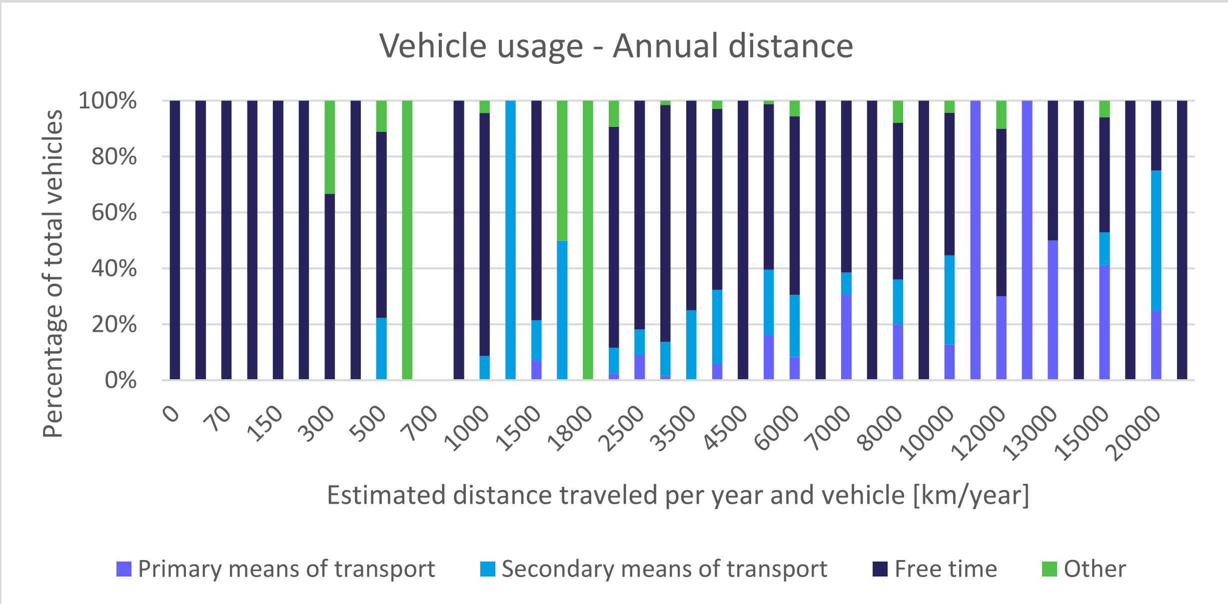

Figure 22: Influence of vehicle usage to the number of modifications (top: by total number of vehicles, bottom: as a percentage).

A comparison of the results by country has also been done, for the five countries that had the most questionnaires completed, e.g., Austria, Greece, Germany, Italy, and Slovenia (see Table 5). In addition, since results from both online and in-person questionnaires from Greece were available, it was decided to check the consistency between the results of these two types of questionnaires, so as to be able to draw valid conclusions. As shown in Table 6, the results were close and therefore consistent. Top answers coincide, as well as the percentages of them are close. As a result, it is possible to conclude that the responses of online questionnaires are trustworthy.

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Table 5: Comparison of questionnaire results by country.

Country	Most Common Answer by Question			
	Age Group	Sex	Vehicle Category	Vehicle Usage
Austria	21-30 (44%)	Male (96%)	Street/Naked/Supersport/Superbike (47%)	Free time (80%)
Greece	31-40 (43%)	Male (99%)	Street/Naked/Supersport/Superbike (38%)	Free time (36%)
Germany	21-30 (31%)	Male (95%)	Street/Naked/Supersport/Superbike (61%)	Free time (93%)
Italy	41-50 (37%)	Male (98%)	Street/Naked/Supersport/Superbike (58%)	Free time (74%)
Slovenia	41-50 (57%)	Male (96%)	Street/Naked/Supersport/Superbike (59%)	Free time (91%)

Table 6: Validation of online results by comparing Greek questionnaires.

Question	Most Common Answer	
	Greek Online Questionnaires	Face-to-face interviews in Greece
Age Group	21-50 (72%)	21-50 (94%)
Sex	Male (98%)	Male (100%)
Vehicle category	Street/Naked/Supersport/Superbike (35%)	Street/Naked/Supersport/Superbike (41%)
Vehicle registration year	2007-2016 (47%)	2007-2016 (56%)
Vehicle bought	Used (81%)	Used (77%)
Vehicle usage	Free time Secondary means of transport (69%)	Free time Secondary means of transport (68%)
Modification	After-market silencer After-market air filter (26%)	After-market silencer After-market air filter (34%)
Modification category	Exhaust (27%)	Exhaust (41%)

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4.2 Effects of most common tampering methods on pollutant and noise emissions

After identifying the most common tampering techniques, a qualitative approach was used for the documentation of the effects that these modifications may have on pollutant, carbon dioxide (CO_2), and noise emission levels. More specifically, in Table 7 it is documented whether an increase or decrease is observed on the emission levels of carbon oxide (CO), CO_2, nitrogen oxides (NO_x), hydrocarbon (HC), and noise after applying each tampering technique, or whether the technique does not have a significant effect. The modifications are presented by the same order that resulted from the questionnaire responses (see Table 2), that is, from the most common to the less common tampering techniques. Table 7 also includes some comments explaining the effects of each modification.

In the scope of this study, after-market parts refer to both certified and non-certified parts that can be applied to vehicles and are not manufactured by OEMs. In addition, since – as described below – some modifications are more complex and there are different ways to implement them, it was decided that the most likely case would be examined for each modification. Note that the presence of control systems, such as a lambda closed loop control system, may also abate the effects of some modifications (commented below where relevant).

The followed can be concluded for each modification:

- The most frequent modification turned out to be the after-market silencer. Using a non-certified and even in some cases a certified after-market silencer leads to higher noise emissions, while they do not affect the pollutant emissions. In some vehicles, the catalyst is part of the silencer and therefore replacing the original silencer with an after-market one is equal to the removal of the catalyst (see point about Catalyst removal).
- The replacement of the air filter may improve the air flow in the intake by allowing more air into the engine. While this can lead to a decrease in fuel consumption and a consequent decrease in CO_2 emissions, the subsequent changes in the gas dynamics in the intake may lead to a small or no increase in CO, NO_x and HC emissions and an increase in noise produced by the vehicle.
- The replacement of the fairing may result in an increase in the total weight of the vehicle. In addition, after-market fairing may not be designed for having optimal air resistance characteristics. As a result, fuel consumption and CO_2 emissions may be increased, while pollutant and noise emissions of the vehicle are not affected.
- While there is a great variety of modifications that can be made to the ECU, the most common one aims to achieve a richer combustion in order to increase power. A richer combustion results in better fuel efficiency and lower NO_x emissions, but higher HC and CO ones. Engine speed may also be increased, leading to higher noise emissions.
- The removal of a vehicle's silencer leads to a significant increase in its noise emissions. In some vehicles, the catalyst forms part of the silencer and thus, the removal of the original silencer is equal to the removal of the catalyst (see point about Catalyst removal).
- By removing the catalyst of a vehicle, pollutant emissions are significantly increased, while noise levels may slightly be increased. The removal of the catalyst results in lower backpressure and as a result the exhaust gases flow easier and the fuel consumption and CO_2 emissions decrease.
- Modifying the exhaust manifold results in a negligible effect on pollutant emissions. In some cases, exhaust back pressure may be reduced, which consequently leads to a slightly lower fuel

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consumption and CO_2 emissions. Such modifications allow exhaust gases to flow more freely and therefore higher power and torque can be achieved by the engine. This also results in an increase in the noise emissions of the vehicle.

- The final drive gear can be replaced either by a longer one, which reduces engine speed, or a shorter one, which increases acceleration. The latter is the most probable modification, which may result in increased fuel consumption and consequently CO_2 emissions, while the noise emissions of the vehicle may show a non-relevant increase.
- By using after-market spark plugs, better combustion conditions may be achieved and therefore lower CO and HC emissions, as well as a decrease in the fuel consumption and CO_2 emissions of the vehicle.
- There are various systems that can be used to adjust the exhaust valve, as well as various ways to place them in the vehicle. The most common one is placing them after the catalyst. While driving the vehicle with the valve opened, noise emissions increase significantly, whereas having the valve closed does not affect the noise levels. The dB killer is often present on after-market exhausts and can lead to higher noise emissions if removed, which is easily done.
- The removal of fairing parts of a vehicle may lead to a slight increase in its fuel consumption and CO_2 emissions. Since the original parts are designed to achieve optimum drag coefficient, by removing them the air resistance of the vehicle may be increased.
- After-market ECUs are mainly applied to pre-Euro 5 vehicles and their effects may vary. The most probable reason to modify the ECU is to achieve a richer combustion to increase power and noise. This results in higher pollutant emissions, as well as an increase in fuel consumption and CO_2 emissions.
- The replacement of a vehicle’s clutch with an after-market one does not affect its pollutant or noise emission levels.
- By porting the cylinder head, the intake air flow is increased, and leaner combustion conditions are achieved. As a result, in vehicles that do not have lambda closed loop control, CO and HC emissions show a slight decrease, while NO_x ones may increase.
- The objective of removing the air filter of a vehicle is to increase the air/fuel ratio in the intake and achieve better combustion. As a result, higher NO_x and noise emissions, while lower HC and CO ones may be expected.
- The replacement of the camshafts is most probably done with a view to increasing the torque of the engine at high rotational speeds. In this way, more power and richer combustion (in vehicles without lambda closed loop control) can be achieved and therefore an increase in pollutant, CO_2, and noise emission levels.
- The objective of increasing an engine’s displacement is to increase both power and speed of the vehicle. However, by modifying the engine so fundamentally, the vehicle is expected to deviate from its original optimal operating parameters. Therefore, pollutant emissions may increase. By achieving more power, higher fuel consumption and noise emission levels may also be achieved.
- The aim of removing the engine speed limiter is to achieve higher engine speed and higher maximum vehicle speed. When the engine operates at lower engine speeds, there is no effect on emissions. However, higher engine speeds may lead to richer combustion. In this way, CO, HC, and noise emissions may increase, while the consequent increase in power also results in an increase in fuel consumption and CO_2 emissions.

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- The replacement of the carburetor with an after-market one leads to richer combustion and therefore higher fuel consumption and CO, HC, CO_2 emissions, while lower NO_x ones. In addition, more power is achieved, which results in an increase in noise emissions.
- By reducing the weight of the flywheel, the total weight of the vehicle is reduced and therefore a slight reduction in fuel consumption and CO_2 emissions is achieved. Higher acceleration is enabled, leading to higher noise levels.
- The replacement of the ignition coils is done in order to achieve better combustion and therefore a slight decrease in CO and HC emissions, as well as in fuel consumption and CO_2 emissions.
- The gearbox gears may be replaced either by longer or shorter ones. The latter case is the most probable and it is done so as to increase the rotational speed of the engine. As a result, fuel consumption, CO_2 and noise emissions may be increased.
- The replacement of the fuel injectors is done in order to inject more fuel. In this way, the combustion conditions become richer and therefore CO, HC and CO_2 emissions are increased. In addition, more power is achieved, which leads to an increase in noise.
- By reducing the weight of the crankshaft, the total weight of the vehicle is reduced and therefore a slight reduction in fuel consumption and CO_2 emissions is achieved.
- By increasing the wheelbase, the total weight of the vehicle is increased, which leads to an increase in fuel consumption and CO_2 emissions as well.

The following table may be used as a guide and contribute to identifying tampering methods easier and reducing the detrimental effects of LVs on air and noise pollution.

Table 7 (1/5): Effects of most common tampering methods in pollutant and noise emission levels.

No. Ranking	Category	Modification	Effect in CO	Effect in CO_2	Effect in NOx	Effect in HC	Effect in noise level
1	Exhaust	After-market silencer	-	-	-	-	↑↑
			Comment: Non-certified and even some certified replacement exhausts can lead to higher noise emissions, while they do not affect pollutant emissions. In some vehicles, the catalyst forms part of the silencer and thus, the replacement of the silencer is equal to removing the catalyst (see point 6).				
2	Air Intake	After-market air filter	-/↑	↓	-/↑	-/↑	↑/↑↑
			Comment: Replacing the air filter can lead to better air flow in the intake, and therefore, better fuel consumption (decrease in CO_2 emissions). However, the subsequent changes in the gas dynamics in the intake may lead to a small or no increase in CO, NO_x, and HC emissions, and an increase in noise.				

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Table 7 (2/5): Effects of most common tampering methods in pollutant and noise emission levels.

No. Ranking	Category	Modification	Effect in CO	Effect in CO_2	Effect in NOx	Effect in HC	Effect in noise level
3	Fairing	After-market fairing	-	↑	-	-	-
			Comment: Replacing the fairing can lead to an increase in the total weight of the vehicle, as well as in its air resistance, and therefore, an increase to fuel consumption.				
4	ECU and electronics	Software modifications to ECU	↑	-/↑	↓	↑	↑
			Comment: A great variety of modifications can be made to the ECU. The most common one aims to achieve a richer combustion and increase power, which leads to lower NO_x emissions, but higher HC, CO, and CO_2 ones. Engine speed may also be increased, leading to higher noise emissions.				
5	Exhaust	Removal of silencer, silencer modifications	-	-/↓	-	-	↑↑↑
			Comment: Removing a vehicle's silencer leads to a significant increase in noise. In some vehicles, the catalyst forms part of the silencer and thus, the removal of the silencer is equal to the removal of the catalyst (see point 6).				
6	Exhaust	Catalyst removal	↑↑↑	↓	↑↑	↑↑↑	↑
			Comment: By removing the catalyst of a vehicle, pollutant emissions are increased significantly, while noise levels may increase, but not as much. As the exhaust gases flow easier due to the lower backpressure, the fuel consumption and thus the CO_2 emissions decrease.				
7	Exhaust	Modifications to exhaust manifold (tubes)	-	-/↓	-	-	↑
			Comment: The effect on pollutant emissions is negligible. In some cases, exhaust back pressure may be reduced, leading to a slightly lower fuel consumption and therefore lower CO_2 emissions. By allowing the exhaust gases to flow more freely, higher power and torque can be achieved, which can lead to higher noise levels.				
8	Transmission	After-market final drive gear	-	↑	-	-	-/↑
			Comment: There are 2 different reasons behind modifying the final drive gear: either the objective is to have a longer final gear, which reduces engine speed (least probable), or a shorter one, which increases acceleration (most probable).				

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Table 7 (3/5): Effects of most common tampering methods in pollutant and noise emission levels.

No. Ranking	Category	Modification	Effect in CO	Effect in CO_2	Effect in NOx	Effect in HC	Effect in noise level
9	ECU and electronics	After-market spark plugs	↓	↓	-	↓	-
			Comment: The replacement of the spark plugs is done in order to achieve better combustion conditions and therefore a decrease in both emissions and fuel consumption.				
10	Exhaust	Adjustable exhaust valve/dB killer	-	-/↓	-	-	↑↑
			Comment: There are various systems that can be used to adjust the exhaust valve, as well as various ways to place them in the vehicle. The most common one is after the catalyst. While driving with the valve opened, noise emissions increase significantly, whereas having the valve closed does not affect the noise levels. The dB killer is often present on after-market exhausts and can lead to higher noise emissions if removed, which is easily done.				
11	Fairing	Removal of fairing parts	-	-/↑	-	-	-
			Comment: By removing fairing parts, which are designed to achieve optimum drag coefficient, the air resistance of the vehicle is increased and therefore its fuel consumption.				
12	ECU and electronics	After-market ECU	↑/↑↑	↑↑	↑	↑↑	↑
			Comment: After-market ECUs are mainly applied to pre Euro 5 vehicles and their effects may vary. The most probable reason to modify the ECU is to achieve a richer combustion to increase power and noise. This leads to an increase in emissions, as well as in fuel consumption.				
13	Transmission	After-market clutch (slip clutch or regular)	-	-	-	-	-/↑
			Comment: Replacing the clutch does not affect the pollutant or noise emission levels of a vehicle.				
14	Engine	Porting cylinder head	-/↓	-	-/↑	-/↓	-
			Comment: By porting the cylinder head, the intake air flow is increased, and leaner combustion conditions are achieved. As a result, in vehicles that do not have lambda closed loop control, CO and HC emissions show a decrease, while NO_x ones may show an increase.				

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Table 7 (4/5): Effects of most common tampering methods in pollutant and noise emission levels.

<table>
<tr><th>No. Ranking</th><th>Category</th><th>Modification</th><th>Effect in CO</th><th>Effect in CO_2</th><th>Effect in NOx</th><th>Effect in HC</th><th>Effect in noise level</th></tr>
<tr><td rowspan="2">15</td><td rowspan="2">Air Intake</td><td rowspan="2">Air filter removal</td><td>↓</td><td>-</td><td>↑</td><td>-/↓</td><td>↑/↑↑</td></tr>
<tr><td colspan="5">Comment: The removal of the air filter of a vehicle is done in order to increase the air/flow ratio and lead to better combustion. As a result, an increase in NO_x and noise emissions can be expected, while HC and CO ones may decrease.</td></tr>
<tr><td rowspan="2">16</td><td rowspan="2">Engine</td><td rowspan="2">After-market camshafts</td><td>↑</td><td>↑</td><td>↑</td><td>↑</td><td>↑</td></tr>
<tr><td colspan="5">Comment: Replacing the camshafts is most probably done with a view to increasing the torque at high rotational speed. This leads to more power and richer combustion (in vehicles without lambda closed loop control) and therefore an increase in pollutant emissions and can lead to higher noise emission levels as well.</td></tr>
<tr><td rowspan="2">17</td><td rowspan="2">Engine</td><td rowspan="2">Increased engine displacement (after-market cylinder, pistons, rods, etc.)</td><td>↑</td><td>↑</td><td>↑</td><td>↑</td><td>-/↑</td></tr>
<tr><td colspan="5">Comment: The objective of increasing an engine's displacement is to increase both power and speed of the vehicle. However, by modifying the engine so fundamentally, the vehicle is expected to deviate from its original optimal operating parameters. Therefore, pollutant emissions may increase. By achieving more power, fuel consumption and noise levels may also increase.</td></tr>
<tr><td rowspan="2">18</td><td rowspan="2">ECU and electronics</td><td rowspan="2">Engine speed limiter removal</td><td>-/↑</td><td>-/↑</td><td>-</td><td>-/↑</td><td>-/↑</td></tr>
<tr><td colspan="5">Comment: The removal of the engine speed limiter is done to achieve higher engine speed and thus higher maximum vehicle speed. When the engine operates at lower engine speeds, there is no effect on emissions. However, higher engine speeds may lead to richer combustion and an increase in both pollutant and noise emissions. The increase in power also leads to a slight increase in CO_2 emissions.</td></tr>
<tr><td rowspan="2">19</td><td rowspan="2">Fuel System</td><td rowspan="2">After-market carburetor</td><td>↑↑</td><td>↑↑</td><td>↓</td><td>↑↑↑</td><td>↑</td></tr>
<tr><td colspan="5">Comment: By replacing the carburetor, the combustion conditions become richer, and therefore CO, HC, and CO_2 emissions are increased, while NO_x ones are decreased. In addition, more power is achieved, which can lead to an increase in noise.</td></tr>
</table>

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Table 7 (5/5): Effects of most common tampering methods in pollutant and noise emission levels.

No. Ranking	Category	Modification	Effect in CO	Effect in CO_2	Effect in NOx	Effect in HC	Effect in noise level
20	Engine	Flywheel weight reduction	-	-/↓	-	-	-/↑
			Comment: By reducing the weight of the flywheel, a slight reduction in fuel consumption is achieved. Higher acceleration is enabled, leading to higher noise levels.				
21	ECU and electronics	After-market ignition coils	-/↓	-/↓	-	-/↓	-
			Comment: The replacement of the ignition coils is done in order to achieve better combustion and therefore a slight decrease in both emissions and fuel consumption.				
22	Transmission	After-market gearbox gears	-	↑	-	-	-/↑
			Comment: There are 2 different ways to modify the gearbox gears; either by using longer gears (least probable) or shorter ones (most probable). The latter is done so as to increase the rotational speed of the engine, which increases noise and fuel consumption.				
23	Fuel System	After-market fuel injectors	↑	↑	-	↑	↑
			Comment: The replacement of the fuel injectors is done in order to inject more fuel. As a result, the combustion conditions become richer, and therefore CO, HC and CO_2 emissions are increased. In addition, more power is achieved, which can lead to an increase in noise.				
24	Engine	Crankshaft weight reduction	-	-/↓	-	-	-
			Comment: By reducing the weight of the crankshaft, a slight reduction in fuel consumption is achieved.				
25	Transmission	Wheelbase increase	-	-/↑	-	-	-
			Comment: By increasing the wheelbase, the total weight of the vehicle is also increased, which leads to an increase in fuel consumption as well.				

*(-): no effect, (↑): increase (on a scale of one to three), (↓): decrease (on a scale of one to three), (-/↑): slight or no increase, (-/↓): slight or no decrease.

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5 Conclusions

Tampering poses a severe problem that may lead to harmful effects, affecting not only the environment, but human health as well. It further contributes to the deterioration of pollutant and noise emission performance, especially of L-category vehicles. LVs have historically faced more relaxed emission standards than other vehicle categories and are a known source of noise complaints due to higher peak noise levels compared to other types of vehicles. The aim of this report was to describe the most common LV tampering techniques that are currently applied within the EU and to assess their impacts on both air and noise pollution by using a qualitative approach.

From the present study, it can be concluded that the most common LV tampering method in the EU is the replacement of the original silencer of a vehicle with an after-market one. In addition, most tampering attempts aim to modify the exhaust system of a vehicle, while LV tampering is mostly motivated by the need to increase engine power. The modifications that seem to have the most significant effects on pollutant emissions are the removal of the catalyst, using an after-market ECU or an after-market carburetor. On the other hand, regarding noise impact, the removal of the silencer, using an adjustable exhaust valve or removing the air filter of a vehicle seem to affect noise levels most significantly.

It is imperative to take anti-tampering measures with a view to preventing such modifications and decreasing their negative impacts. The main output of this work is a qualitative table documenting the effects of the most common LV tampering methods on pollutant (CO, NOx, HC), CO_2, and noise emission levels. The effect summary table could be used as guidelines to contribute to identifying different tampering types more effectively and reducing the detrimental effects of LVs on air and noise pollution.

The present study is part of the L-vehicles Emissions and Noise mitigation Solutions (LENS) project, funded from the EU's Horizon Europe research and innovation programme under grant agreement No 101056777. LENS is a three-year project that focuses on assisting law enforcement and regulatory authorities to reduce the contribution of LVs to air and noise pollution.

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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Appendix

Common methods of tuning and modifying motorcycles and other L-category vehicles in Europe

This questionnaire is for those who regularly use or own a motorcycle, or another L-category vehicle (3-wheeler, ATV, mini-car etc.), which has at least one, or more modifications on them.

This survey is being carried out as part of the LENSproject funded by the Horizon Europe Research and Innovation Programme under Grant Agreement number 101056777. The aims of this survey are to identify the most common methods of tuning/modifying motorcycles and other L-category vehicles and find out how frequently these take place in different countries within Europe.

This questionnaire is voluntary. All gathered data will be used only within the scope of the LENS project and will be anonymized. Motorcycle info will also be anonymized. No individual information will be shared with law enforcement of any kind.

For more information:

LENS website

LENS in twitter

LENS in linkedin

Figure 23 (1/8): Online questionnaire user interface used in the scope of the LENS project.

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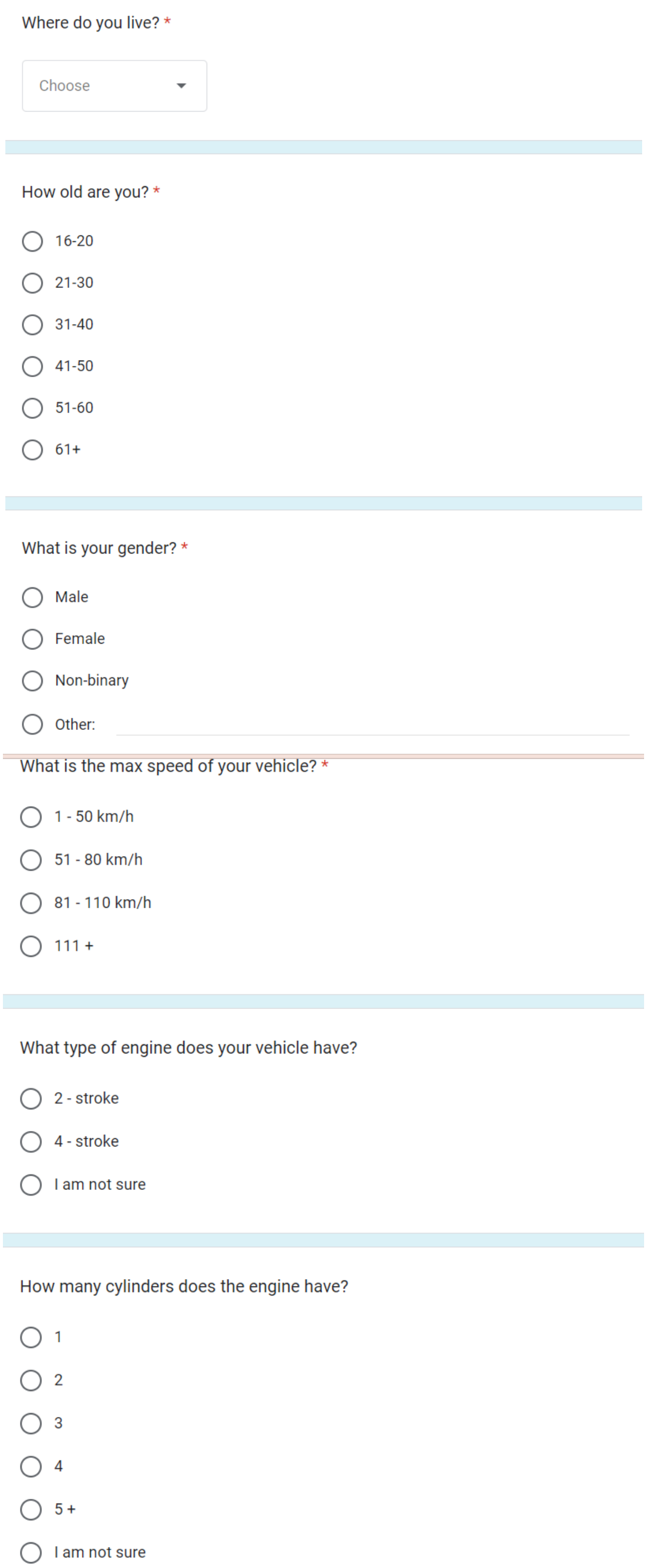

Where do you live? *

Choose

How old are you? *

- 16-20
- 21-30
- 31-40
- 41-50
- 51-60
- 61+

What is your gender? *

- Male
- Female
- Non-binary
- Other:

What is the max speed of your vehicle? *

- 1 - 50 km/h
- 51 - 80 km/h
- 81 - 110 km/h
- 111 +

What type of engine does your vehicle have?

- 2 - stroke
- 4 - stroke
- I am not sure

How many cylinders does the engine have?

- 1
- 2
- 3
- 4
- 5 +
- I am not sure

Figure 23 (2/8): Online questionnaire user interface used in the scope of the LENS project.

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Engine displacement of your vehicle's engine: *

- ◯ 1 - 125 cc
- ◯ 126 - 300 cc
- ◯ 301 - 785 cc
- ◯ 786 - 1.071 cc
- ◯ 1.072 - 1.357 cc
- ◯ 1.358 + cc

What is the max power of your vehicle's engine?

- ◯ 1 - 10 Hp
- ◯ 11 - 30 Hp
- ◯ 31 - 60 Hp
- ◯ 61 - 90 Hp
- ◯ 91 + Hp
- ◯ I am not sure

What type of transmission does your vehicle have?

- ◯ Chain
- ◯ CVT
- ◯ Belt
- ◯ Shaft
- ◯ I am not sure

Your vehicle was bought:

- ◯ New
- ◯ Used

The brand and model of your vehicle is (e.g. Honda CBR, Yamaha R1):

If you don't want to answer this question, please fill in the following one!

Your answer

The country/area origin of your vehicle brand is (e.g. USA, China,Germany or North America, Asia,Europe):

You don't have to answer this if you answered the previous question!

Your answer

Figure 23 (3/8): Online questionnaire user interface used in the scope of the LENS project.

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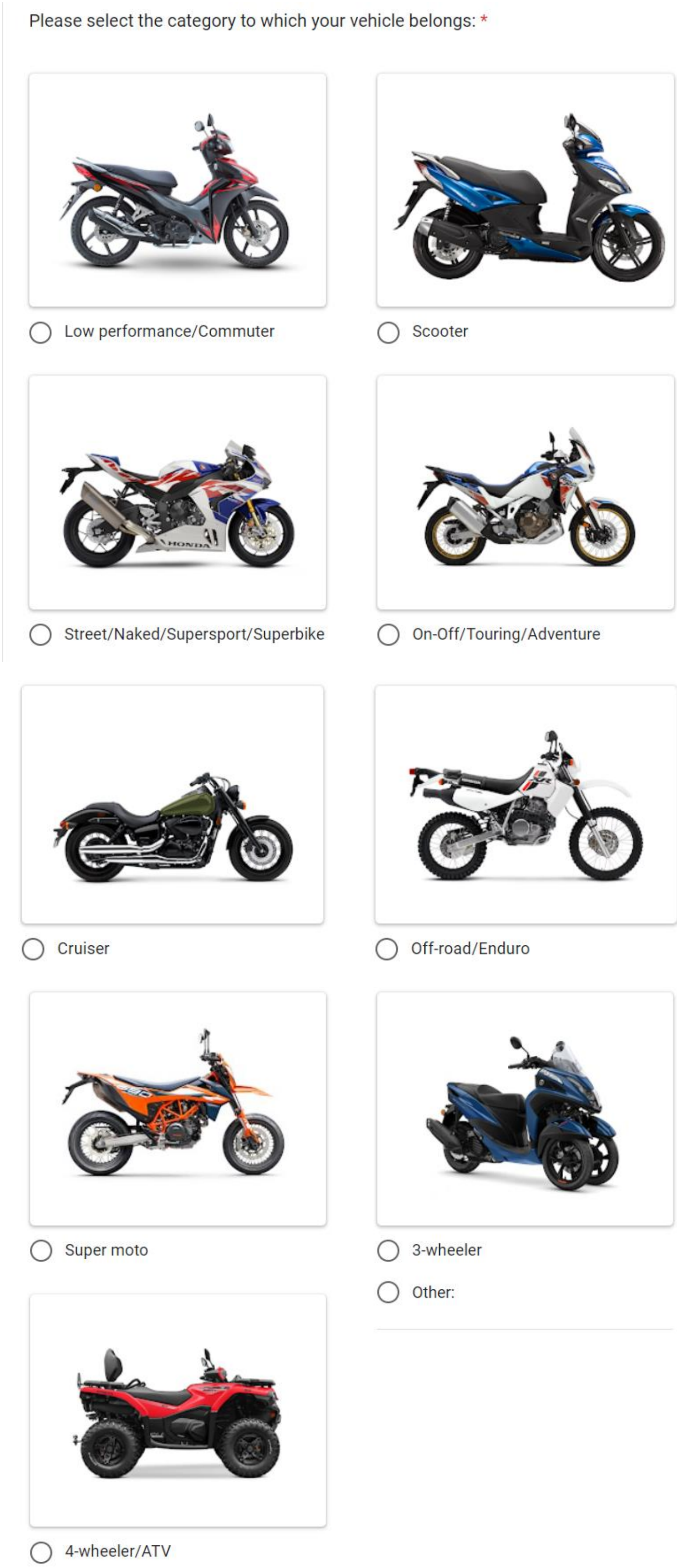

Figure 23 (4/8): Online questionnaire user interface used in the scope of the LENS project.

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What is the current mileage of your vehicle (ODO)?
Please enter distance in [km]

Your answer

How much do you estimate that you drive the vehicle every year?
Please enter distance in [km]

Your answer

Vehicle registration year (1st registration): *

- ◯ Up to 1998
- ◯ 1999 – 2006
- ◯ 2007 – 2016
- ◯ 2017 – 2020
- ◯ 2021 – 2023

Most frequent usage of the vehicle: *

- ◯ Primary means of transport
- ◯ Secondary means of transport
- ◯ Free time
- ◯ Other: ____________

Figure 23 (5/8): Online questionnaire user interface used in the scope of the LENS project.

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Have you modified or tuned your vehicle (Excluding the regular service, any possible repairs, or replacement of parts with OEM/original ones)? If so, please select what have you modified: *

(After-market = non-OEM)

- [ ] No modifications
- [ ] Exhaust system - Removal of silencer, silencer modifications
- [ ] Exhaust system - After-market silencer
- [ ] Exhaust system - Catalyst removal
- [ ] Exhaust system - Adjustable exhaust valve / db-killer
- [ ] Exhaust system - Modifications to exhaust manifold (tubes)
- [ ] Air intake - Air filter removal
- [ ] Air intake - After-market air filter
- [ ] Fuel system - After-market fuel injectors
- [ ] Fuel system - After-market carburetor
- [ ] ECU and electronics - After-market ECU
- [ ] ECU and electronics - Software modifications to ECU
- [ ] ECU and electronics - Engine speed limiter removal
- [ ] ECU and electronics - After-market spark plugs
- [ ] ECU and electronics - After-market ignition coils
- [ ] Engine - Porting cylinder head
- [ ] Engine - After-market camshafts
- [ ] Engine - Flywheel weight reduction
- [ ] Engine - Increased engine displacement (after-market cylinder, pistons, rods, etc.)
- [ ] Engine - Crankshaft weight reduction
- [ ] Transmission - After-market final drive gear
- [ ] Transmission - After-market gearbox gears
- [ ] Transmission - After-market clutch (slip clutch or regular)
- [ ] Transmission - Wheelbase increase
- [ ] Fairing - Removal of fairing parts
- [ ] Fairing - After-market fairing
- [ ] Other: ____________

Figure 23 (6/8): Online questionnaire user interface used in the scope of the LENS project.

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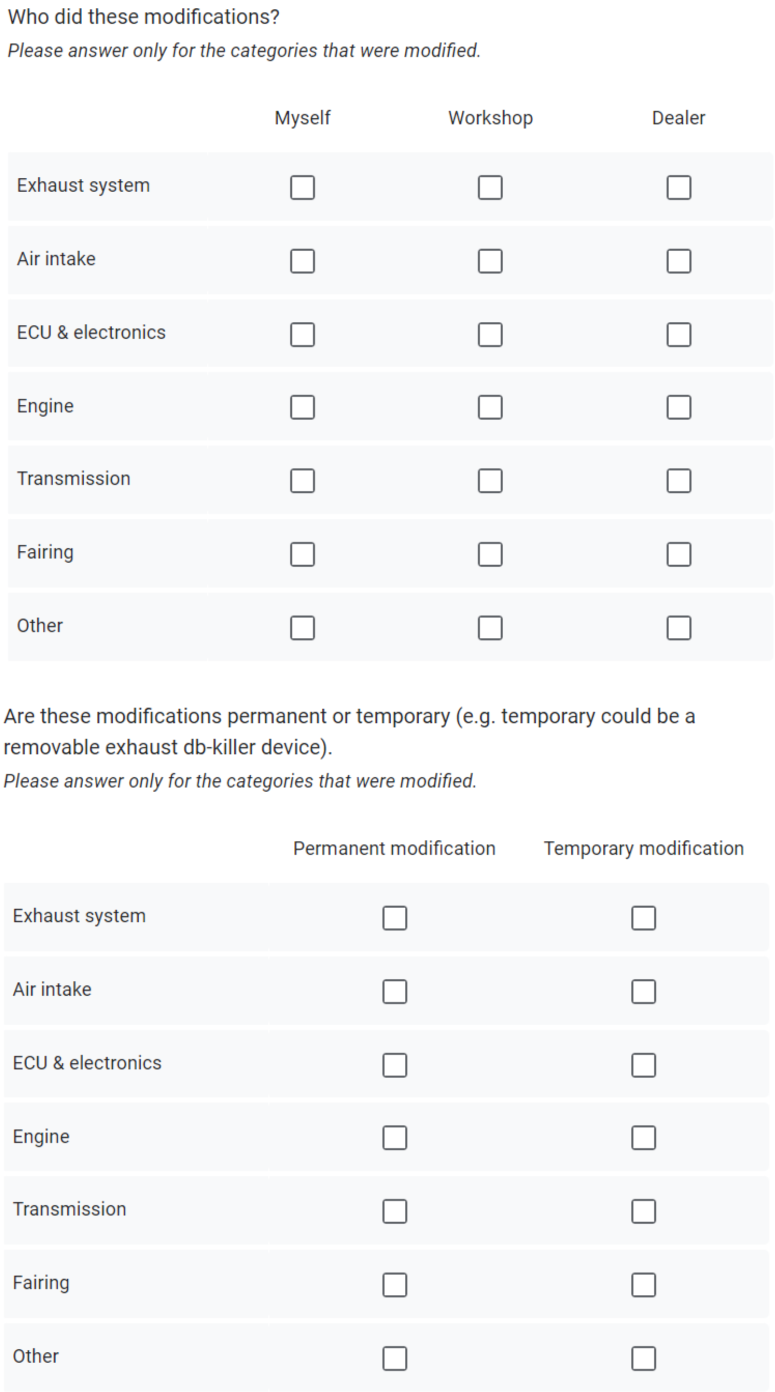
Who did these modifications?

Please answer only for the categories that were modified.

	Myself	Workshop	Dealer
Exhaust system	☐	☐	☐
Air intake	☐	☐	☐
ECU & electronics	☐	☐	☐
Engine	☐	☐	☐
Transmission	☐	☐	☐
Fairing	☐	☐	☐
Other	☐	☐	☐

Are these modifications permanent or temporary (e.g. temporary could be a removable exhaust db-killer device).

Please answer only for the categories that were modified.

	Permanent modification	Temporary modification
Exhaust system	☐	☐
Air intake	☐	☐
ECU & electronics	☐	☐
Engine	☐	☐
Transmission	☐	☐
Fairing	☐	☐
Other	☐	☐

Figure 23 (7/8): Online questionnaire user interface used in the scope of the LENS project.

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What was the reason you did these modification?

Please answer only for the categories that were modified. You may enter multiple reasons for each modification.

	For more power	For better fuel economy	For better appearance	For better sound	For better handling
Exhaust system	☐	☐	☐	☐	☐
Air intake	☐	☐	☐	☐	☐
Fuel system	☐	☐	☐	☐	☐
ECU & electronics	☐	☐	☐	☐	☐
Engine	☐	☐	☐	☐	☐
Transmission	☐	☐	☐	☐	☐
Fairing	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

Figure 23 (8/8): Online questionnaire user interface used in the scope of the LENS project.

Table 8 (1/2): Number of responses by country.

Country	Online questionnaires	Face-to-face interviews	Total
Austria	192	0	192
Greece	60	61	121
Germany	58	0	58
Italy	57	0	57
Slovenia	23	0	23
Spain	11	0	11
The Netherlands	8	0	8
Belgium	7	0	7
Other	6	0	6
Sweden	5	0	5
Czech Republic	3	0	3

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Table 8 (2/2): Number of responses by country.

Country	Online questionnaires	Face-to-face interviews	Total
Cyprus	3	0	3
France	2	0	2
Finland	2	0	2
Slovakia	2	0	2
Bulgaria	1	0	1
Estonia	1	0	1
Lithuania	1	0	1
Malta	1	0	1
Poland	1	0	1
Portugal	1	0	1

Table 9: Number of responses by age group.

Age group	Online questionnaires	Face-to-face interviews	Total
16-20	13	9	22
21-30	137	64	201
31-40	116	109	225
41-50	101	52	142
51-60	63	6	68
61+	17	0	17

Table 10: Number of responses by gender.

Sex	Online questionnaires	Face-to-face interviews	Total
Male	426	61	487
Female	14	0	14
Non-binary	4	0	4
Other	1	0	1

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Table 11: Number of responses by maximum vehicle speed.

Max speed	Online questionnaires	Face-to-face interviews	Total
1-50	2	0	2
51-80	4	0	4
81-110	15	5	20
111+	424	54	478

Table 12: Number of responses by engine type.

Type of engine	Online questionnaires	Face-to-face interviews	Total
2-stroke	22	0	22
4-stroke	417	56	473
Not sure	6	0	6

Table 13: Number of responses by number of cylinders.

Number of cylinders	Online questionnaires	Face-to-face interviews	Total
1	102	10	112
2	234	24	258
3	8	3	11
4	94	21	115
5+	2	0	2
Not sure	4	1	5

Table 14: Number of responses by engine displacement.

Engine displacement	Online questionnaires	Face-to-face interviews	Total
1-125	15	3	18
126-300	17	4	21
301-785	137	23	160
786-1,071	148	18	166
1,072-1,357	114	11	125
1,358+	14	0	14

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Table 15: Number of responses by maximum power.

Max power	Online questionnaires	Face-to-face interviews	Total
1-10	8	1	9
11-30	17	5	22
31-60	48	11	59
61-90	116	11	127
91+	251	33	284
Not sure	7	0	7

Table 16: Number of responses by transmission type.

Transmission	Online questionnaires	Face-to-face interviews	Total
Chain	383	52	435
CVT	5	0	5
Belt	18	2	20
Shaft	32	4	36
Not sure	7	0	7

Table 17: Number of responses by type of vehicle.

Vehicle bought	Online questionnaires	Face-to-face interviews	Total
New	158	14	172
Used	286	47	333

Table 18 (1/2): Number of responses by vehicle category.

Vehicle category	Online questionnaires	Face-to-face interviews	Total
Street/Naked/Supersport/Superbike	118	25	243
On-Off/Touring/Adventure	99	18	117
Super Moto	51	4	55
Off-road/Enduro	28	1	29
Scooter	9	9	18
Cruiser	21	0	21

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Table 18 (2/2): Number of responses by vehicle category.

Vehicle category	Online questionnaires	Face-to-face interviews	Total
Low performance/Commuter	5	4	9
4-wheeler/ATV	3	0	3
Other	11	0	11
3-wheeler	0	0	0

Table 19 (1/2): Number of responses by annual distance travelled.

Annual distance travelled	Online questionnaires	Face-to-face interviews	Total
0	2	0	2
50	1	0	1
70	1	0	1
100	2	0	2
150	1	0	1
200	2	0	2
300	3	0	3
400	1	0	1
500	8	1	9
600	1	0	1
700	1	0	1
850	1	0	1
1.000	23	0	23
1.200	1	0	1
1.500	12	2	14
1.700	1	0	1
1.800	0	1	1
2.000	39	5	44

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Table 19 (2/2): Number of responses by annual distance travelled.

Annual distance travelled	Online questionnaires	Face-to-face interviews	Total
2.500	9	2	11
3.000	60	8	68
3.500	7	1	8
4.000	28	6	34
4.500	1	0	1
5.000	69	12	81
6.000	34	3	37
6.500	1	0	1
7.000	19	7	26
7.500	3	0	3
8.000	21	4	25
9.000	3	0	3
10.000	42	6	48
11.000	1	0	1
12.000	10	0	10
12.500	2	0	2
13.000	4	0	4
14.000	1	0	1
15.000	15	3	18
17.000	1	0	1
20.000	3	1	4
27.000	1	0	1

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Table 20: Number of responses by vehicle registration year.

Vehicle registration year	Online questionnaires	Face-to-face interviews	Total
Up to 1998	49	2	51
1999-2006	63	8	71
2007-2016	144	34	178
2017-2020	94	10	104
2021-2023	95	7	102

Table 21: Number of responses by vehicle usage.

Vehicle usage	Online questionnaires	Face-to-face interviews	Total
Primary means of transport	44	16	60
Secondary means of transport	61	23	84
Free time	322	16	338
Other	18	1	19

Table 22: Number of responses by modification category.

Category	Total
Exhaust	615
ECU and electronics	265
Air Intake	245
Fairing	194
Transmission	146
Engine	121
Fuel System	39

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Table 23: Number of responses by number of modifications.

Number of modifications	Total
1	121
2	103
3	84
4	50
5	34
6	24
7	19
8	18
9	5
10	3
11	6
12	8
13	3
14	4
15	0
16	1
17	0
18	1
19	0
20	0
21	0
22	0
23	0
24	0
25	1

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Table 24 (1/2): Number of responses by modification.

Modification	Online questionnaires	Face-to-face interviews	Total
After-market silencer	280	45	325
After-market air filter	178	33	211
After-market fairing	126	15	141
Software modifications to ECU	105	12	117
Removal of silencer, silencer modifications	88	12	100
Catalyst removal	82	14	96
Modifications to exhaust manifold (tubes)	72	22	94
After-market final drive gear	69	7	76
After-market spark plugs	53	9	62
Adjustable exhaust valve/dB killer	54	0	54
Removal of fairing parts	50	3	53
After-market ECU	40	4	44
After-market clutch (slip clutch or regular)	40	3	43
Porting cylinder head	29	6	35
Air filter removal	30	4	34
After-market camshafts	22	5	27
Increased engine displacement (after-market cylinder, pistons, rods, etc.)	24	3	27
Engine speed limiter removal	24	2	26
After-market carburettor	22	2	24

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Table 24 (2/2): Number of responses by modification.

Modification	Online questionnaires	Face-to-face interviews	Total
Flywheel weight reduction	15	3	18
After-market ignition coils	12	4	16
After-market gearbox gears	11	4	15
After-market fuel injectors	11	4	15
Crankshaft weight reduction	11	3	14
Wheelbase increase	12	0	12

Table 25: Number of responses by who did the modifications.

Who did the modifications	Total
Myself	811
Workshop	409
Dealer	135
Combination of them	27

Table 26: Number of responses by modification type.

Type of modification	Total
Permanent	805
Temporary	356

Table 27: Number of responses by reason behind modifications.

Reason behind modifications	Total
More Power	823
Better Sound	366
Better Appearance	231
Better Handling	145
Fuel Economy	186

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Table 28: List of non-signifiicant modifications based on questionnaire responses.

Non-significant modifications
LED lighting
Custom paint
Mirrors, different seat, and general modifications for the vehicle to be more user friendly
Headlight, Indicators, Seat, Crash bars
Heating grips
Top case, paniers, heated handgrips, tank bag, …
Top box, windshield
Handlebars
New handlebar
Pneumatic horn, higher handlebar, side cases and back case
Mirrors, Indicators, Licence Plate Holder, Crash Pads
Sticker
Mirrors, Numberplateholder, Seat, blinker
Luggage
Seat
USB charger
Crash bars, fog lights
Handlebar
Heated grips
Headlight, licence plate holder
Mainly optical parts
Windshild, blinker
OEM side bags
After-market Blinkers, Mirrors, Numberplatecarrier and Windshield
Front + Rear Blinkers / Seat / LED HLU

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