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CHARACTERIZATION OF THE NOISE EMISSIONS OF A PASSENGER VEHICLE

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ABSTRACT
One of the main sources of noise pollution in cities is vehicle traffic. In this paper a characterization of the noise emission of a passenger vehicle has been carried out. With this aim a representative driving route for noise emission has been defined in order to study the influence of the driver typology and vehicle type. Therefore, this investigation has been developed in three phases:

Firstly, usual driving in an urban area like Madrid has been characterized with a specific driving route. In addition, several vehicle models with great presence in the existing fleet of cars have been selected. Several drivers have covered the driving route at different times of the day and previous parameters have been measured in each test in order to determine average values of behavior.

Secondly, the type of vehicles and drivers influence in noise emissions has been deeply analyzed. To achieve this aim a sample of vehicles has been instrumented to obtain physical measurements of the variables that can influence the noise emission level. Positions, velocities, accelerations (longitudinal and lateral) and time have been analyzed using a GPS sensor. Parameters such as, engine speed, engine load, throttle position and engine temperature have been studied through the vehicle CAN BUS and a set of microphones has measured the emitted noise in several points of the vehicle.

In order to study the ecological and safety impact in urban and interurban roads by means of the measurement of noise emissions the analysis of the driver behaviour is of paramount importance.

To conclude, the previous data has been analyzed and noise equivalent levels have been identified with different test configurations.

INTRODUCTION
One of the main sources of noise pollution in cities is traffic noise. Around an 80% of the city noise is produced by vehicles.

In fact, noise pollution has been the origin of social tension between economic development and quality of life. Due to the fact that nowadays cities are constantly growing and the rising number of vehicles, sustainable acoustic environment has become a key issue and a technological challenge. Despite the efforts made to reduce the noise emissions of individual vehicles, noise disturbance has not diminished in equal measure because it is been offset, among other things, by the growth of the vehicle fleet (1).

Noise level of a vehicle must be measured according to a test procedure shown in the current legislation Directive 70/157/EEC (2). The vehicle, before obtaining its approval must be subjected to this test. If the noise emitted by the vehicle exceeds the maximum noise level regulated by the current legislation the vehicle will not obtain the type approval. The values of the maximum allowable noise level have been diminishing gradually along the past years. Although the maximum noise level has been decreased its effect on the overall traffic noise has not been very important. The reason is that the real noise level emitted by a real vehicle during real driving conditions has not been properly represented in the approval tests. Approval tests include specific driving conditions such as transient acceleration and deceleration.

In order to measure the noise emissions of a vehicle during real driving conditions a pattern test must be established. This pattern test will allow control over the parameters that might influence such noise emissions and, most important of all, be able to reproduce in the same way the measuring conditions any time the test is performed.

However, this goal is very ambitious when one considers that noise emission is modified depending on the type of driver, his driving, the type of traffic, the size and type of vehicle, road conditions, etc.

The pattern test designed to measure vehicle gas emissions aims to assess and weight different features that represent the real behavior of a vehicle, such as engine speed or engine load.

It is necessary to establish a type of test that allows to weight different characteristics that represent the real behavior of a vehicle from the noise emissions point of view (3). In order to do it, several working parameters must be determined, taking into account different characteristics related to types of drivers, vehicle maintenance, driving conditions, etc.

SAMPLE VEHICLES SELECTION

In this paper only noise emission levels of passenger vehicles have been studied. These vehicles are usually classified into different segments according to their size, which corresponds well with their level of power and refinement and, therefore, their price.

The selection of the sample vehicles has been carried out by analyzing the Spanish vehicle fleet and selecting vehicles that clearly represent the current Spanish stock. Based on this criterion the following vehicles have been selected:

- Two B-segment vehicles (compact cars): These types of vehicles are the most popular in urban areas. Compact cars usually have a small engine, of up to 73 kW power and low fuel consumption. Even, drivers that have two vehicles one of them is usually a compact car. Analyzing car registrations in Spain for 2009, this segment corresponds to 30% of the fleet (4).
- Two C-segment vehicles (midsize cars): These vehicles are also quite common in urban traffic. They have a mid-power engine of around 100 kW. Analyzing vehicle registrations in 2009, this segment corresponds to 29% of the fleet.
- Two D-segment vehicles: These vehicles are usually provided with powerful engines and are part of urban traffic. Analyzing vehicle registrations in 2009, this segment corresponds to 15% of the Spanish fleet.

For each segment, a diesel engine model and a petrol engine model have been selected. It seems reasonable to analyze both engines, although, due to economical reasons, in every segment 70% of the registered cars in Spain have diesel engine (and only 30% have petrol engine). All of the vehicles used during the tests use manual transmission gearboxes.

After analyzing vehicle registration statistics published by ANFAC (4), brands and models have been selected. According to these data, the selected vehicles for each segment are:

- B-segment: Seat Ibiza with petrol engine (it will be denoted as V1) / Seat Ibiza with diesel engine (denoted as V2)
- C-segment: Renault Megane with diesel engine (V3) / Ford Focus with petrol engine (V4)
- D-segment: Audi A4 with diesel engine (V5) / Mercedes C180 with petrol engine (V6)

DRIVING ROUTE SELECTION

In order to select the most appropriate driving route a set of criteria has been selected:

- Representativeness: According to the report "European Transport Policy and Sustainable Mobility" (5), by the European Commission for Energy and Transport, over 75% of the EU population lives in urban areas and around a fifth of all miles traveled in the EU are urban trips. From the previous data it is clear why urban transport has so great importance in the overall mobility. According to the people mobility the selected driving route must be representative of the average route that a driver covers during his daily displacements in urban ways (commuting, doing arrangements for daily activities, etc.) This is a potential 80% of trips in a big city and therefore has a high impact on noise pollution. The same report concludes that the average trip of a driver in urban roads is between 8 and 12 km. This data has also been taken into account for the selection of the driving route.
- Traffic density: Traffic levels in the selected area are high but without reaching a jam such that traffic speeds were unrepresentative.
- Noise emissions level: The area has also been chosen according to the "Strategic Noise Map of the City of Madrid (6). This document, prepared by the City of Madrid

(Figure 1), represents data relative to measured noise equivalent levels, surpassing of limit values, number of residential, scholar or sanitary buildings in each area and population in each area. The area has been chosen trying to assure that people suffer high noise emission levels due to traffic, as it is necessary for the analysis.

Figure 1: Day Equivalent Continuous Level in the Carabanchel District

Taking into account the above criteria, two driving routes have been defined: one urban and one interurban.

Urban driving route: Within the Carabanchel District, according to the available noise maps (Figure 1), the driving route (Figure 2) is defined by the lines of higher levels of equivalent sound pressure.

Figure 2: Map of the selected driving routes

The driving route has a day equivalent continuous noise level between 70 and 75 dB(A) and a traffic density between 20000 and 40000 vehicles per day.

The selected driving route includes roads limited, generally, to 50 km/h, but some sections are limited to only 30 km/h. In addition, 50% of the driving route runs through a two-lane with two- ways streets, and the other 50% runs through four- lanes two-ways streets. The driving route is 8500 m long and has 25 traffic lights.

Interurban driving route: In order to study the noise level at greater speeds, an interurban driving route has been selected using the same criteria. This driving route consists of a three-lane with two- ways stretch of the M40 ring road, between kilometers 22 and 27. This stretch has a day equivalent continuous noise level over 75 dB(A) and a traffic density between 100000 and 150000 vehicles per day. The speed in the M40 is limited to 100 km/h and the considered driving route is 8600 m long.

USED EQUIPMENT

The following measuring equipment has been used to measure and record physical parameters in order to analyze the behavior of the vehicle:

- Acquisition and Recording System: IMC Cronos PL. PULSE LabShop.
- GPS Positioning System: Vbox Lite II of 10 Hz
- CAN BUS System: Module TMCAN-AOI4-Eth - ODB2. ELM317 probe
- Microphones & Conditioners: Shure MX183 Microphones. Phantom Fonestar 48 V

CAN-BUS (Controller–area network) is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer. it is a message-based protocol, designed specifically for automotive applications.

Figure 3 shows the used equipment and Figure 4 the position of the microphones. The first microphone (MIC-1) is placed inside the engine compartment, near the entrance of the inlet valve. The second one (MIC-2) is near the rear wheel, opposite to the exhaust pipe.

Figure 3: Used equipment

Figure 4: Microphones installed in engine compartment and vehicle chassis underbody

MEASURED PARAMETERS

Table 1 shows the parameters that have been recorded with the measuring devices for further analysis. Every signal is acquired and processed by the CRONOS PL and recorded in a notebook PC.

Table 1: Registered parameters

Parameter	Equipment	Units
Engine speed	TMCAN	rpm
Engine load	TMCAN	%
Throttle position	TMCAN	%
Engine microphone	PULSE	dB
Wheel microphone	PULSE	dB
Latitude	VBox	Grades
Longitude	VBox	Grades
Altitude	VBox	m
Distance	VBox	m
Speed	VBox	km/h
Longitudinal acceleration	VBox	m/s^2
Lateral acceleration	VBox	m/s^2
Time	VBox	s

TEST PROCEDURE

For each vehicle documentation is generated, such as vehicle features, tires, etc. Afterwards, the microphones and other measurement equipment are installed in the vehicle. In order to begin the recording of the measurements always at the same point of the circuit a reference point was established. Tests have been carried out with five different drivers: two women and three men. In addition, one of the drivers performed an extra test driving in an aggressive style so as to reduce travel time and measure this driving style. The aggressive style is based on high engine speeds and selected gears lower than usual in order to increase the mobility of the vehicle with continuous lane changes. Non aggressive drivers performed the circuit driving in the same way as they usually do and taking into account traffic conditions. The results of these drivers allow us to compare different behaviors in order to select a representative average driver or standard driver.

Tests have been carried out at several hours (morning and afternoon), in several days of the week and under different weather conditions. During driving three people are inside the car: the driver and two people operating the measurement equipments. Once the circuit is finished, the vehicle returns to the university lab to change the driver and store the acquired data in the workgroup server.

Each vehicle is tested during two days, to get the car from the car rental office, install, calibrate and test the instrumentation, drive the vehicle to the test area, drive the vehicle along urban and interurban circuits, return to the campus and change driver 5 times, retire the instrumentation and leave back the vehicle to the car rental office.

Each combination vehicle-driver takes about 40 minutes to complete both circuits, depending on the traffic. Each car covers a distance of 111 km to complete 6 tests (one per driver). The complete study has taken 666 km of measurements, not considering other passages.

VEHICLES AND DRIVERS BEHAVIOR ANALYSIS ALONG TO THE URBAN CIRCUIT

In this study the influence of some driving variables over some defined driving interest parameters, and the influence of the driving interest parameters over the vehicle emitted noise, are analyzed.

The considered driving variables, introduced and directly modified in the course of the study, are: driver age (ages varying from 20 to 45 years), driving license experience (varying from 2 to 25 years), driver sex, engine type (petrol - diesel) and driving condition (5 drivers driving with a standard driving style and driver 6, which drove along the circuit with an aggressive driving style).

The considered driving interest parameters, resulting from the test measurements, are: vehicle speed, engine angular speed and selected gear.

The emitted noise in the engine compartment and near the vehicle's wheels has been accounted in terms of 1 second equivalent level ($L_{eq, 1s}$) evolution, equivalent level L_{eq} and level histograms.

Because of space limitation, in this paper it will only be shown results coming from D-segment vehicles, the most frequent in the American market (7-8). Vehicle V5 has diesel engine, and vehicle V6 has petrol one, so it will be possible to see the differences between the most popular engine types relative to noise emissions for the same kind of vehicle.

Acquired driving interest parameters data have been analyzed for each vehicle and driver combination. The three parameters best defining the driver behavior have been selected, building vehicle speed histograms, engine speed histograms and gear time charts.

Average graphs for the behavior of drivers 1 to 5 and graphs for the driver 6 are depicted. The reason of gathering together drivers 1 to 5 in this paper is that the results are quite similar between them, mainly from the point of view of their behaviour, and the results have been considered representative of a standard driver. The comparison of the behaviour parameters shows clearly the similarity between the drivers 1 to 5 and the difference with the 6^{th} driver. It is not possible to show all the results because of the limited length of the paper, but it is clear the behaviour similarity between these five drivers by looking at their speeds, engine speeds and percentages of the time spent in each gear. Figures 6-13 are included below in order to compare the behaviour of an average driver and an aggressive driver for diesel and petrol vehicles.

As an example, Figure 5 shows average speed in the urban circuit for every vehicle and driver. It can be seen that average speeds do not differ greatly from one driver to another, with no dependence in sex or age, showing a slight tendency to increase with the size of the vehicle. It is also noted that driver 6, who has driven more aggressively than the others, has achieved an average speed slightly above the rest for every vehicle. However, the difference is so insignificant that this type of driving does not provide significant benefits; it only means an increase in consumption and noise emissions. Similar results can be found analyzing the behavior of engine speed or gearing for different drivers.

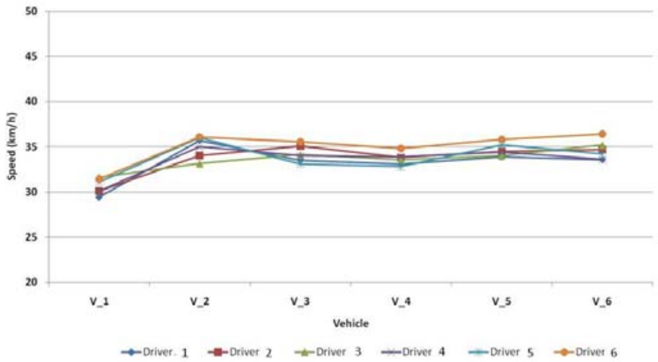

Figure 5: Average speed for each vehicle and driver..

In Figure 6 the speed histogram for vehicle V6 driven by both drivers, average driver and aggressive driver, is depicted. This graph gives an idea of the amount of time spent in a certain speed.

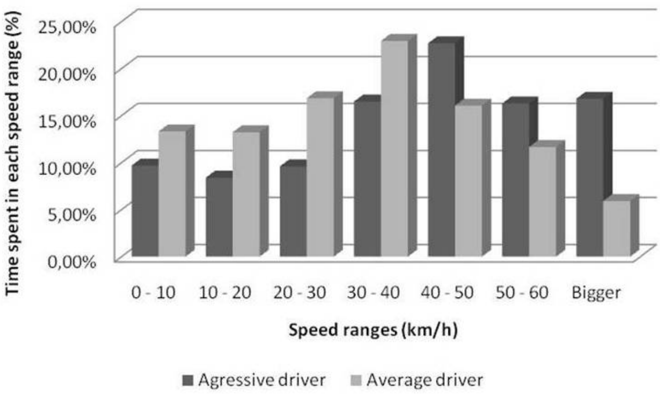

Figure 6: Speed histogram for the vehicle V6.

In Figure 7 the engine speed histogram for vehicle V6 is shown. It can be seen that a standard driving style tends to keep the engine speed around 2000 rpm and an aggressive driving style keeps an engine speed higher (2500-3000 rpm).

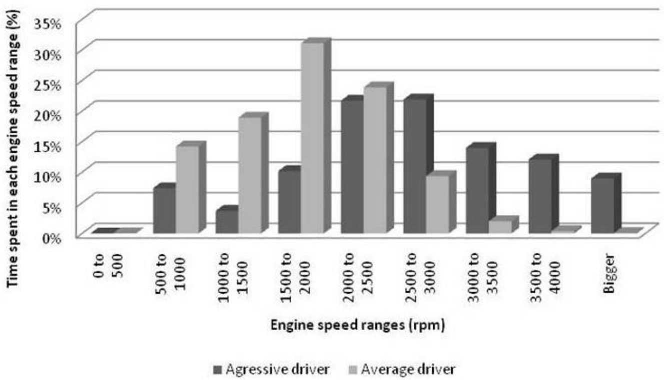

Figure 7: Engine speed histogram for the vehicle V6.

In Figure 8 the time spent in each gear in percentage for the vehicle V6 driven by an average driver is shown.

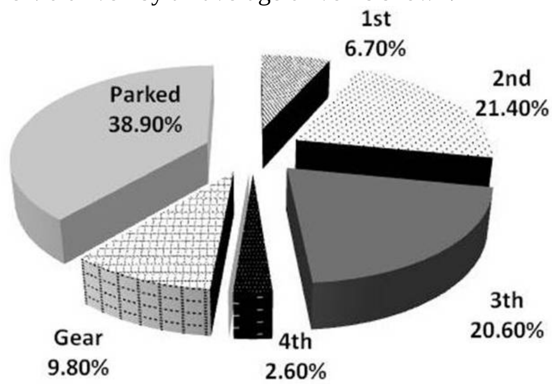

Figure 8: Percentage of the time spent in each gear for the vehicle V6 – Average driver.

The same chart has been obtained for the aggressive driver, as shown in Figure 9.

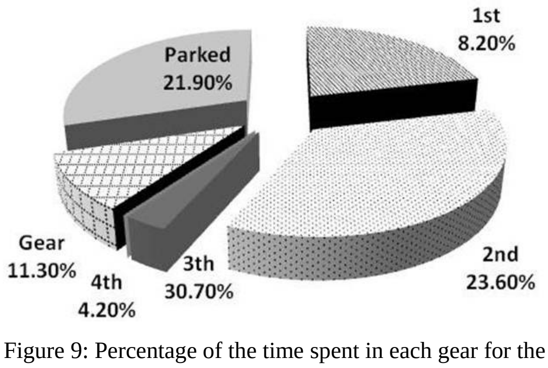

Figure 9: Percentage of the time spent in each gear for the vehicle V6 – Agressive driver.

Results for vehicle V5 are depicted in Figures 10 to 13: Figures 10-11 for both drivers, Figure 12 for average driver and Figure 13 for the aggressive driver. In Figure 10 the speed histogram for vehicle V5 is depicted. This chart gives an idea of the amount of time spent in a certain speed.

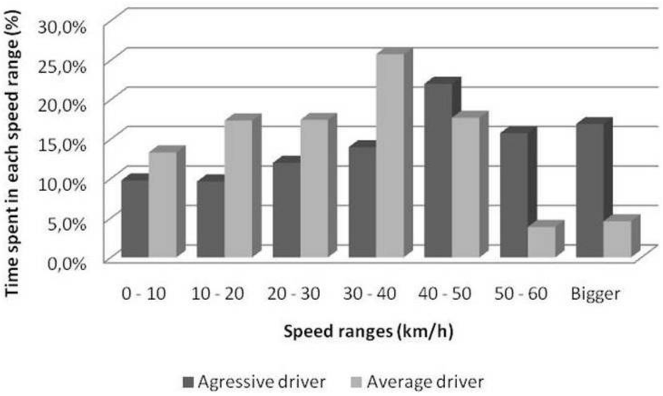

Figure 10: Speed histogram for the vehicle V5.

In Figure 11 the engine speed histogram for vehicle V5 driven is shown. It can be seen that a standard driving style tends to keep the engine speed around 1500 rpm and an aggressive driving style keeps an engine speed clearly in a higher range (2500-3000 rpm).

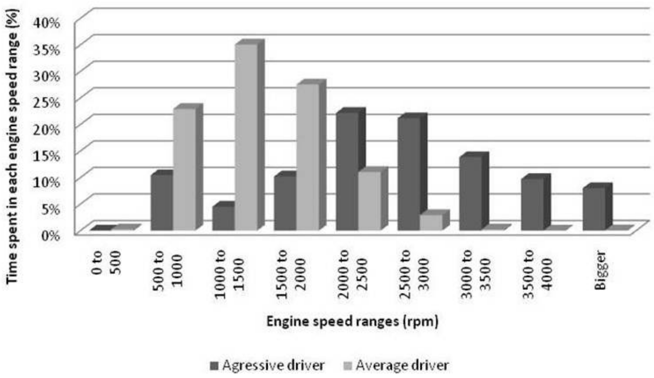

Figure 11: Engine speed histogram for the vehicle V5.

In Figure 12 the time spent in each gear in percentage, is shown.

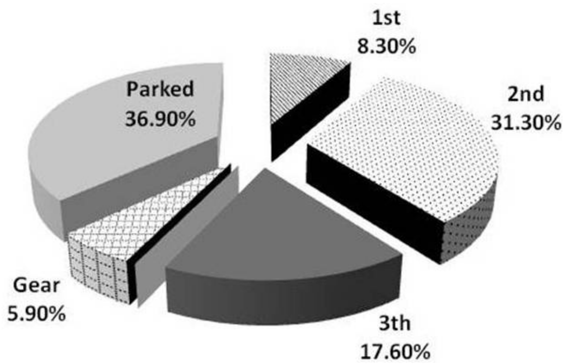

Figure 12: Percentage of the time spent in each gear for the vehicle V5 – Average driver.

The same chart has been obtained for the aggressive driver, as shown in Figure 13.

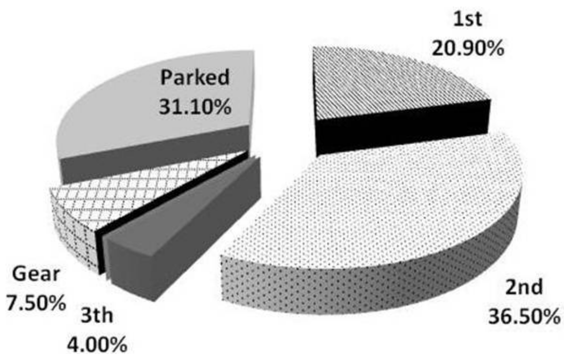

Figure 13: Percentage of the time spent in each gear for the vehicle V5 – Aggressive driver.

NOISE EMISSIONS ANALYSIS IN BOTH CIRCUITS

To analyze the influence of the considered driving variables and driving interest parameters over emitted noise $L_{eq,1\,s}$ graph from microphone 1 (engine compartment) and Levels Histogram were built for each vehicle–driver combination. Since drivers 1 to 5 appeared to show very similar results, noise measured data is depicted for just one of them (referred as "standard driver") against the driver 6 ("aggressive driver"). Figures 14-16 for the standard driver and Figures 17-19 for the aggressive driver.

Previously, to start the measurements both microphones were adjusted with the B&K 4231 sound calibrator at 94 dB. Then signals were recorded through template of PULSE system. To analyze the influence of the considered driving variables and driving interest parameters over emitted noise. First are represented the evolution of the $L_{eq,1s}$ of each of the microphones and for each vehicle throughout both circuits, for aggressive and average drivers, is shown in Figures 14-17. It can be seen an obvious sound level decreases when the vehicle is in a stop, or increases when the vehicle is accelerating. Notice that engine noise is higher for the diesel than for the petrol vehicle, mainly at the minima (neutral gear, in the traffic lights of sense changing). As expected, the wheel noise is more correlated with the speed of each vehicle. Thus, wheel noise of aggressive driver is significantly higher than average driver.

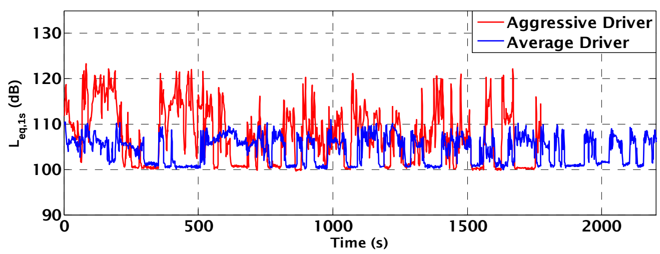

Figure 14: Results of the $L_{eq,1s}$ graph of the vehicle V5 – Engine noise – Aggressive and Average drivers.

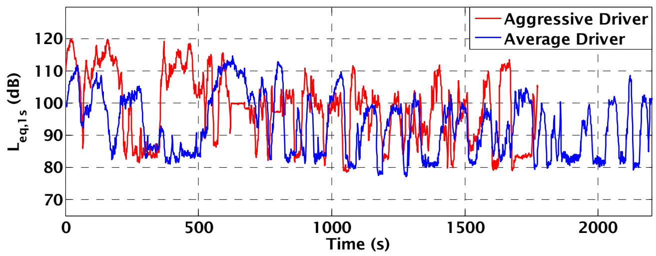

Figure 15: Results of the $L_{eq,1s}$ graph of the vehicle V5 – Wheel noise – Aggressive and Average drivers.

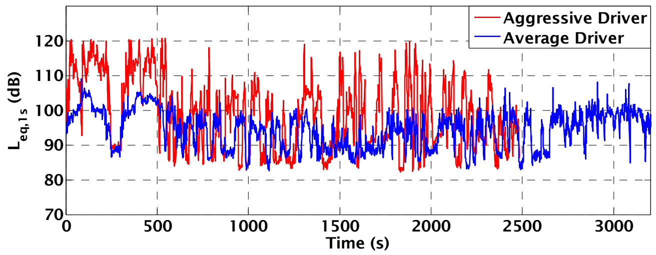

Figure 16: Results of the $L_{eq,1s}$ graph of the vehicle V6 – Engine noise – Aggressive and Average drivers.

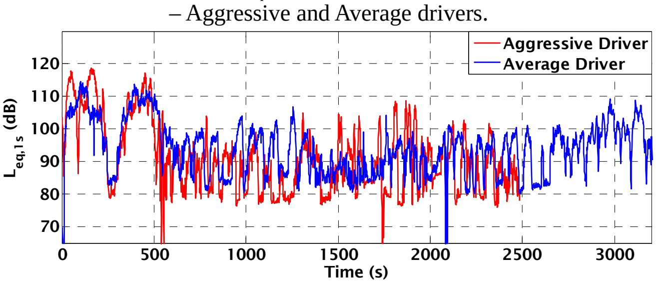

Figure 17: Results of the $L_{eq,\ 1s}$ graph of the vehicle V6 – Wheel noise – Aggressive and Average driver.

Second are plotted the level histograms of time history of aggressive driver in comparison with average driver for the engine and wheel noises of diesel vehicle, are shown in Figures 18-19. Basically the first peak in the plots represents when the vehicle is out of gear. The histogram of aggressive driver is displaced towards higher levels in both cases. As expected, this displacement is more significant for the engine noise

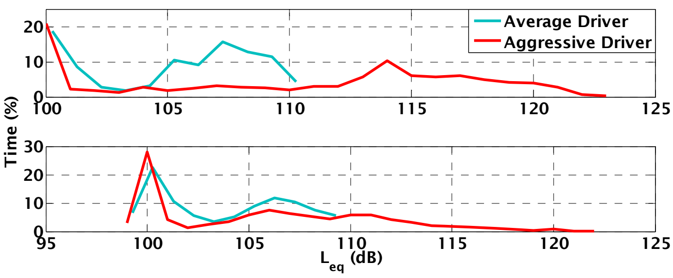

Figure 18: Level histograms graphs of the vehicle V5- Engine noise – Interurban (top) and urban (below) circuits – Aggressive and Average drivers.

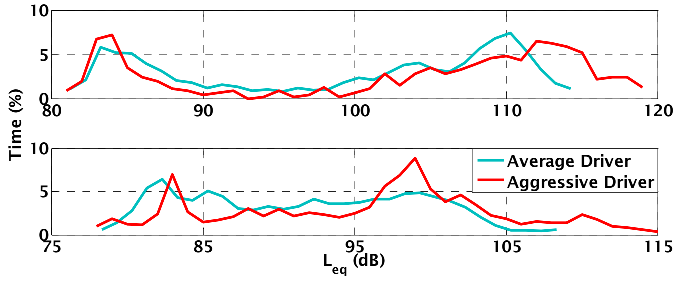

Figure 19: Level histograms graphs of the vehicle V5- Wheel noise – Interurban (top) and urban (below) circuits – Aggressive and Average drivers.

Analogous results can be shown for vehicle V6, as shown in Figures 20- 21.

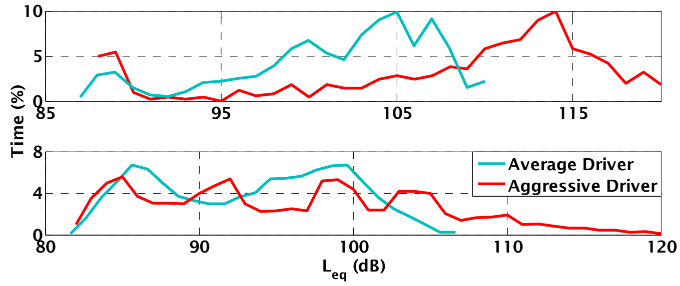

Figure 20: Level histograms graphs of the vehicle V6 - Engine noise – Interurban (top) and urban (below) circuits – Aggressive and Average drivers.

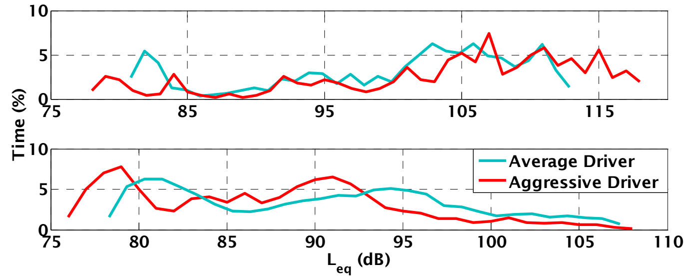

Figure 21: Level histograms graphs of the vehicle V6 - Wheel noise – Interurban (top) and urban (below) circuits – Aggressive and Average drivers.

The analysis of the obtained results show:

- It is possible to find differences in the $L_{eq,1\ s}$ graph and in the Levels Histogram for the aggressive driver compared to the standard one in the same vehicle, which indicate that the driving condition influences the emitted noise level.
- It is very easy to associate the spectrogram shape to the vehicle characteristic noise.

Table 2: Global equivalent levels L_{eq} for engine and wheel noises for every driver for petrol vehicle.

Driver	Engine Noise (dB)		Wheel Noise (dB)	
1	104.2	$\langle L_{eq1-5} \rangle$	108.5	$\langle L_{eq1-5} \rangle$
2	99.6	103.1	105.5	105.4

3	102.2		102.6	
4	104.6		101.5	
5	103.4		105.2	
6	111.7		108.1	

Table 2 compares driver 6 (Aggressive) L_{eq} with drivers 1-5 L_{eq}. Aggressive driver is 8-9 dB noisier for the engine noise and 2-3 dB noisier for the wheel noise.

Table 3: Global equivalent levels L_{eq} for engine and wheel noises for every driver for diesel vehicle.

Driver	Engine Noise (dB)		Wheel Noise (dB)	
1	107.0	$\langle L_{eq1-5} \rangle$ 107.2	107.8	$\langle L_{eq1-5} \rangle$ 106.6
2	105.9		104.0	
3	107.9		107.9	
4	107.6		105.6	
5	107.1		107.0	
6	114.5		110.4	

In Table 3 it can be found again that the aggressive driver is 7-8 dB noisier for the engine noise and 3-4 dB noisier for the wheel noise. It can finally be deduced that depending on the engine type a vehicle can emit 7-9 dB more in the engine and 2-3 dB more in the wheels if it is driven in a “noisy” way. However, it is important to highlight that the results of wheel noise are less representative than engine noise because of the kind of used circuit. Wheel noise has been measured in conditions of “open circuit”, in real traffic, and it wasn’t possible to control the conditions. On other hand it is well known that wheel noise is mainly related to wheel speed and the speed is not very different between all of drivers in urban circuit. From this point of view, the results of engine noise are considered more representatives of the driver behaviour.
Analyzing the results, the confirmation that global noise levels and Levels Histograms are useful to discriminate between different driving ways. And it is especially useful to identify noisy drivers.

CONCLUSIONS

Comparing results in the driving parameters for the different driving variables combinations, some conclusions can be obtained:

- There is no influence of the driver age (ages varying from 20 to 45 years, driving license experience varying from 2 to 25 years) over the considered driving interest parameters.
- There is no influence of the driver sex (3 males, 2 females) over the considered driving interest parameters.
- There is no big influence of the engine type (Petrol - Diesel) over the considered driving interest parameters. Maybe a small influence over the engine speeds, but not very significant.
- Driving condition (Aggressive - Normal) has definitely influence over engine speed and selected gear, but not significantly on vehicle average speed. Maximum speed and speed dispersion can be nevertheless influenced.

Regarding obtained noise measurements, it can be concluded:

- The most relevant parameter to compare noise emissions between an average driver and an aggressive driver is the engine noise.
- Wheel noise is significantly higher for aggressive drivers than for normal driving conditions. This difference is more remarkable for diesel vehicles than for petrol ones.
- Engine noise is also significantly higher for aggressive driving conditions, especially for petrol vehicles because they have a higher engine speed limit. For low and medium engine speeds, petrol vehicles produce less noise than diesel ones.
- In analogous conditions, engine noise is always higher for diesel vehicles than for petrol ones.
- For diesel vehicles engine noise is higher than wheel noise for any kind of driving conditions (aggressive or not). On the other hand, for petrol vehicles engine noise is almost equal or even lower than wheel noise under normal driving conditions.
- When driving under aggressive conditions engine noise is always higher than wheel noise.
- As can be seen comparing values for drivers 1 to 5 against values for driver 6 in tables 2 and 3, aggressive driving conditions produce higher equivalent noise levels than normal driving conditions.

FUTURE RESEARCH

From the placement of the microphones, it is clear that noise has been measured from its source. Future research includes measuring the attenuation of the hood and computing the contribution to the overall far field noise from the measured near field noise.
The presented tests are included in a deeper project aimed in two directions:

- Developing an onboard system to carry out the kind of tests showed in any vehicle.
- Define a pattern test to determine the noise emission characteristic of a vehicle-driver.

ACKNOWLEDGMENTS

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