# Latest results on the features posed by hybrid and electric vehicles: a special attention about their effect on the noise maps

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## ABSTRACT

The absence of some traditional noise sources and the introduction of new ones, in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), implies new challenges to their noise, vibration and harshness (NVH) signature. As a consequence of their relevant differences with respect to the traditional internal combustion engine (ICE) vehicles, the European COST Action TU1105 "NVH analysis techniques for design and optimization of hybrid and electric vehicles", was defined to acquire, unify and coordinate necessary information about vehicle dynamics, driveability and NVH analysis technologies applied to the novel powertrain designs. Now that the Action has recently finished, this paper collects the main tasks carried out during its four years of lifetime, focusing on the potential influence of EVs in the urban city noise maps.

Keywords: Electric vehicles, hybrid vehicles, noise maps
I-INCE Classification of Subjects Number(s): 13.2.1, 52.3

## 1. INTRODUCTION

Sales of electric (EV) and hybrid electric (HEV) vehicles have been increased in the recent years, becoming more common in urban fleets. This fact is being perceived as a potential solution to the environmental problems arisen with the use of conventional internal combustion engine vehicles (ICEs). From the point of view of the emission of polluting gases, the electric technology is expected to contribute to achieve the goal of reducing CO2 and other gas emissions, which will imply to improve the quality of the air in urban areas, and to reduce the consumption of non-renewable resources. And from the point of view of the sound quality of cities, the alternative vehicles will also provide an improvement, reducing noise pollution coming from traffic flow and impacting positively on the noise maps of the cities.

The increasing incorporation of electric and hybrid vehicles in the automotive market has also enabled to detect that the sound emission and the vibrational characteristics (NVH - Noise, Vibration and Harshness) of that type of vehicles are very different from the features of traditional vehicles. Different aspects cause that road users and pedestrians had to change their perception about pure electric vehicles, or hybrid vehicles running in electric mode. For instance, the low exterior noise emitted by those vehicles can generate dangerous situations due to the low detectability from pedestrians' point of view. But also, new noise sources and vibrations appear now inside the vehicles, which combined with the absence of engine noise, imply that the comfort of driver and passengers could be affected.

These and other considerations were taken into account to create and develop the COST Action TU1105, "NVH analysis techniques for design and optimization of hybrid and electric vehicles" (1). The main objective of the Action was to acquire, unify and coordinate knowledge about the new challenges posed by electric and hybrid vehicles with regards to their acoustical and vibrational behavior, and also to propose and develop new analysis techniques and tools to be used during the

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design phase of such type of vehicles. The project, which was developed within the framework of the COST Action program of the European Union, started its activities in April 2012. During the four years of Action lifetime, it become a large consortium in which 37 entities from 17 countries (including 3 entities from outside Europe) participated, comprising members from the academia and research institutes, to enterprises from the automotive sector and affected collectives. The consortium promoted the transfer of knowledge by means of meetings, training schools, short term scientific missions and dissemination of results at conferences and publications.

In the past a lot of research effort was spent on the development of NVH analysis tools. However, since the noise emission and the vibrational features of these new vehicles change considerably from the traditional vehicles, the NVH analysis techniques traditionally used for the design of ICE vehicles are not always adequate for the design of alternative vehicles. Hence, now that the Action recently finished, this paper gives a general review of the technologies related to noise, vibration and harshness (NVH) developed within the Action framework and that could be usefully applied for the design phase of electric and hybrid vehicles. The outcomes of the Action have resulted from the collaborations among partners, which have provided the presentation of different journal and conference publications, and the compilation and publication of a comprehensive book (2) where all those results are described in detail.

The paper includes a section with the general aspects related to EVs and HEVs regarding the existing electric/hybrid powertrain configurations and also the customers' preferences on those alternative vehicles. After that, it is presented a review of the most recent experimental methods to face the NVH issues related to those vehicles, and also the numerical techniques to simulate their NVH behavior. Finally, the novel sound quality metrics to quantify the perception of the EV and HEV characteristic noise are also referred in the paper, and it is analyzed the effect that a EVs traffic flow would cause on the sound quality of cities, by means of implementing such new traffic noise source on the noise maps calculation models.

## 2. CLASSIFICATION AND CUSTOMERS PERCEPTION OF EVs AND HEVs

The powertrains of alternative vehicles can be classified according to different points of view. Here are usually included the vehicles driven by electrical motors, fuel cell systems and hybrid drives.

On the one hand, within the designation of electric vehicles (EVs), are comprised the vehicles driven by electric motors powered by batteries, range extenders and fuel cell systems. The pure electric vehicles are considered those driven by electric motors powered by batteries, which are charged from the public electric network. Another option is to charge the batteries using a range extender unit, where a generator that charges the batteries is driven by a combustion engine. Finally, the fuel cell vehicles are those in which a hydrogen or methanol fuel cell supplies the electrical energy.

On the other hand, within the designation of hybrid vehicles (HEVs), are comprised the vehicles powered by two different motors (usually an ICE and an electric motor) and their corresponding storage systems. These vehicles can be classified based on their electrification grade and on the way to coupling their engine. Regarding the electrification grade, it can be found start/stop systems, micro hybrid drives, mild hybrid drives and full hybrid drives. Based on the way to coupling their engine, it can be found in-line hybrid drives, parallel hybrid drives, combined hybrid drives, power-split hybrid drives and plug-in drives.

Since HEVs do not have the range limitations of EVs, and also not the drawback of emissions like the pure ICE vehicles, they could be more in line with the consumer's needs and their current and future driving patterns. HEVs combine the advantage of two different propulsion systems, the possibility to drive with zero emission and to drive on long distances. EVs could dominate as pure city- and short distance solutions. Hybrids could be the major solution for sustainable mobility, for individual mobility, for goods transport and for public transport, suitable to enter cities as well. Hence, customer's needs would define the best options for alternative urban and interurban mobility. But also the requirements of other road users – pedestrians, cyclists, other drivers, etc. - should be considered here. In that regard, the results on different customers' expectations studies (3-5) have reflected that customers, and especially those who have never tried an electric vehicle, could be concerned about the price of the alternative vehicles and if could meet their individual mobility requirements. However, these vehicles are seen as environmentally friendly, and their high potential in energy efficiency improvement and delocalization of pollutants emissions are attractive for customers, especially for early adopters.

# 3. ANALYSIS TECHNIQUES FOR THE NVH STUDY OF EVs AND HEVs

As commented before, the alternative vehicles provide new features, different from traditional vehicles' characteristics, which should be considered in order that the EVs and HEVs could be competitive in the automotive market. From the NVH point of view, the main technical challenge comes from the different acoustical and vibrational behaviour of the EVs and HEVs. Such fact involves that the existing NVH techniques are mainly applied to conventional IC vehicles, raising the need to develop new techniques suitable for alternative vehicles. In this section it is presented a review of innovative techniques, both experimental and numerical, for the study of NVH of EVs and HEVs, proposed and developed within the consortium of the TU1105 COST Action.

## 3.1 Experimental Approaches

Compared to traditional internal combustion engines, electric engines translate and enlarge the noise spectrum to a much higher range, changing a priori the testing conditions. In this sense, a relevant current trend is to know how the absence of mechanical sounds can affect the use of the vehicle in urban environments and how electric components, especially at high frequencies, can be perceived by the driver and the passengers. Different experimental approaches have been used and developed for helping to analyze such behavior.

In the first instance, the design of drivetrains and the analysis of structural transmission can be studied by different testing experimental methods. On the one hand, the Transfer Path Analysis (TPA) and the Operational Path Analysis (OPA) methods, commonly used in traditional vehicles, can be satisfactorily applied as well for the design of alternative vehicles, as demonstrated in (6, 7) for improving the acoustic perception in the cabin. Also, the technique of combined input/state estimation was applied on a mechatronic drivetrain in (8), using experimental approaches and numerical models. That research pointed out how moving from a lumped-parameter drivetrain model towards a 1D-3D model would improve the accuracy and enlarge the scope of the applied estimated techniques. As such, the technique can be used to identify and quantify NVH problems related to drivetrain oscillations as a result of the interaction between operational wheel forces and possibly nonlinear drivetrain dynamics. On the other hand, the measurement challenges of the electric motor power source are discussed in (9), pointing out that its signature has totally different frequency zones and characteristic modulation patterns unlike those encountered in ICE vehicles. Finally, a multi-axial dynamic testing procedure using a hydraulic shaker is proposed in (10) to characterize the NVH behavior of vehicles.

Besides, virtual sensing techniques can be used to monitor the driveline conditions and other rotational dynamic systems, as presented in (11). Here is demonstrated that embedded power buffers in EV drivelines can enhance the efficiency of the EV itself.

The study and use of new light materials, which can help for instance for adapting the cabin surrounding and preventing the vibro-acoustical noise transmission, can be addressed by different approaches. In this sense, in (12) it is proposed a novel test setup for fast and easy characterization of acoustic damping materials and lightweight panels. It shows a high versatility, where airborne or structural excitation can be applied and the response can be measured either acoustically or structurally. Furthermore, in (13) it is presented an indirect approach to accurately estimate the mobility matrix of a homogeneous aluminum plate.

Finally, other approaches are proposed for evaluating the interior and exterior NVH behavior of alternative vehicles. For instance, in (14) it is investigated the sustainable noise reduction and enhanced passenger comfort using hybrid diesel-electric urban buses. After some experimental procedures, it is concluded that buses with an electric powertrain offer promising results on interior and exterior noise and on pollutant emissions in the area of public transport. And in (15) it is used the novel On-Board Sound Intensity on EV or HEV method (OBSIe) to evaluate some external aspects as tire/road noise and warning sound signals outside the vehicle, but also in the future to evaluate the noise transmitted inside the cabin with regards to different pavement types, tires or measuring conditions.

## 3.2 Numerical Approaches

Numerical models have been traditionally used for the NVH analysis and design of vehicles. From the Finite Element Method (FEM) and the Boundary Element Method (BEM), both used for structural and acoustical low frequencies analysis, to the Statistical Energy Analysis (SEA) used for high frequencies analysis, and the Multi-Body analysis or 1D System Simulation used for analysis of low frequencies mechanical motion of vehicle systems as suspensions. For the numerical analysis of NVH applied to alternative vehicles, different models and methodologies are proposed.

The FEM modelling for materials design and NVH analysis related to EVs and HEVs is used in (16-18). The first work discusses the developments regarding acoustic resonant metamaterials, to combine lightweight solutions with good NVH properties, to be applied in electrified vehicles. The second study analyses the dynamic behavior of a sandwich laminate structure. And the last one is dedicated to model the behavior of composite materials used in inertial dampers, where vibrational analysis combined with experimental modal identification is applied for damage detection.

The FEM/BEM methods can be also used for the design of warning sound systems applied to EVs. As showed in (19), FEM/BEM is used to validate the loudspeaker configuration of an alerting system. Besides, the potential of the BEM is presented in (20), for the prediction of the sound field generated by alternative vehicles integrating alerting systems in a urban environment.

Finally, other studies as (21), shows a multiphysics NVH simulation of electric drivetrains, applied to the specific problem of a switched reluctance motor.

## 4. PERCEPTION OF EVs AND HEVs AND THEIR INFLUENCE IN NOISE MAPS

The noise levels emitted by an EV are very different from the emitted by an ICE vehicle. Some studies (22, 23) can be found in the literature reporting that such difference could suppose up to 6 dB(A) at 10 km/h. The reduction in the noise levels emitted by an EV could make difficult for pedestrians, and more dramatically for visually impaired ones (24), to detect an approaching EV immerse in the traffic flow due to the masking effect provided by the ambient noise. In that sense, the solution points out to improve the detectability of EVs and HEVs by means of the installation of the so-called Acoustic Vehicle Alerting Systems (AVAS), (25). Those systems usually consist on a loudspeaker or an array of loudspeakers emitting an alerting sound, which could be mounted at different positions, as the front bumper of the vehicle, the wheel arch, under the hood close to the radiator, etc. Given that scenario, national and international authorities (as the European Commission, the US Congress, or the Japanese government) have focused to work on specific legislations and guidelines to regulate the AVAS systems features and behavior. Different features related to the warning sound emissions have been proposed (26), as for instance their audibility, locatability, directivity, attenuation or acceptability. And also, some metrics to evaluate the warning sound systems have been defined, as the minimum sound pressure level (27), or the applicable speed and the pitch frequency shift with acceleration and deceleration (28).

### 4.1 EVs in Noise Maps

The Directive 2002/49/CE (29) has as one of its objectives to provide a common noise indicator and a common methodology for environmental noise calculation, and to legislate the noise emitted by the major noise sources, as the road traffic noise. According to the Directive, EU Member States are required to produce strategic noise maps in their main cities, with the main goal of making a general diagnosis of noise pollution that can lead to action plans, and a noise management that can be implemented in terms of action plans and acoustical planning. There are several models for making noise maps. Some of them use empirical models, based on experimental approaches, but most of the models are based in the physics of propagation of sound outdoors implemented in a theoretical sound power generation model that changes with the characteristics and amount of traffic sources. As none of those models consider the potential presence of alternative vehicles in urban traffic, there is the need of adapting the current traffic noise prediction models in order to include a new variable related to the EVs in the noise maps. In this sense, a study was developed in order to evaluate the effect in a noise map results after considering EVs in its traffic flows.

For this purpose, as a first stage of the study, the noise source represented by an EV was analyzed, carrying on an acoustical characterization of their sound emission. EVs have as main feature the absence of engine noise, so at low driving speeds (i.e., below 35km/h) those could be considered as "silent" vehicles. However, at higher speeds the acoustic emission of an EV is very similar to the emission of a traditional vehicle, since the tire/road noise dominates over the rest of noise sources, for instance the engine noise in an ICE vehicle. That hypothesis was validated by developing an experimental campaign in which different measurements were performed using traditional and electric vehicles (30), and based on the premises of the coast-by and pass-by methods, collected in the Directive 2001/43/CE (31) and in the standard ISO 11819-1 (32) respectively. Such hypothesis will allow including a new variable in the traffic noise prediction models, which quantifies the contribution of EVs in the noise maps, and by assuming that the only noise source in an EV comes from the tire/road interaction.

#### 4.1.1 Updated Traffic Noise Prediction Model

The traffic noise prediction model NMPB ROUTES 2008, generally known as French model (33), was used to evaluate the effect of including the EVs variable for noise maps calculations. According to the guidelines of the method, the noise radiated by a conventional vehicle is divided into two main independent sources, Equation (1): the engine and other mechanical sources, and the source coming from the tire/road interaction where aerodynamic noise is considered as part of that source.

$$L_A\left(V,R,p,a\right)=L_{rolling}\left(V,R\right)+L_{engine}\left(V,p,a\right) \quad (1)$$

Where $L_A$ is the pass-by sound pressure level of the vehicle; $V$ is the vehicle category (considering light vehicles as those with less than 3500kg of weight and heavy vehicles as those with more than 3500kg of weight); $R$ is the road platform surface category; $p$ is the road gradient; $a$ is the traffic flow type (steady speed, acceleration, deceleration); $L_{rolling}$ is the sound pressure level coming from the tire/road interaction; and $L_{engine}$ is the sound pressure level coming from the ICE engine and other mechanical sources.

According to the hypothesis commented before, only tire/road noise source was considered for modeling the noise emitted by EVs. Then, the sound power level emitted by an EV was included in the general calculation algorithm of the French model, obtaining an updated traffic noise prediction model according to Equation (2):

$$\boldsymbol{L}_{\boldsymbol{Awi}}=10*\log_{10}\left(\left(\boldsymbol{E}_{\boldsymbol{vl}}+10*\log_{10}\boldsymbol{Q}_{\boldsymbol{vl}}\right)+\left(\boldsymbol{E}_{\boldsymbol{vh}}+10*\log_{10}\boldsymbol{Q}_{\boldsymbol{vp}}\right)+\left(\boldsymbol{E}_{\boldsymbol{ve}}+10*\log_{10}\boldsymbol{Q}_{\boldsymbol{ve}}\right)\right) \quad (2)$$

Where, considering each category of vehicle $i$ (l – light vehicle, h – heavy vehicle, e – electric vehicle): $L_{Awi}$ is the sound power level emitted by a vehicles traffic flow; $E_{v(i)}$ is the sound power level emitted by each vehicle category; and $Q_{v(i)}$ is the average traffic flow rate for each vehicle category.

#### 4.1.2 Assessment of a EVs Free Field Traffic Flow

Before implementing the updated traffic noise prediction model in a noise map calculation, it was proposed to analyze the noise emitted by a free field traffic lane of vehicles and to assess the variations on the emitted sound pressure levels that would cause to change the proportion of EVs on the traffic flow, according to Equation (3):

$$Q_{li} = Q_l - Q_e \qquad Q_e = N\%{\cdot}Q_l \quad (3)$$

Where $Q_{li}$ is the flow of ICE light vehicles, $Q_l$ is the flow of total light vehicles, $Q_e$ is the flow of EVs and $N$ is the percentage of electric vehicles in the total traffic flow.

For that purpose, it was considered the traffic conditions of a real street located in Elche city, for which it was estimated an average traffic flow of 1260 light ICE vehicles and 150 heavy ICE vehicles, driving at 30km/h, during an evaluation time of one hour, and taking into account a background noise conditions of 45 dB(A) . Then, it was evaluated the effect of gradually substituting, by an EV flow, the flow of light ICE vehicles, considering the above formulas. The results are presented in Figure 1, where it can be observed the differences obtained on the noise emission depending on the percentage of EVs in the flow of light vehicles. The blue line represents the evaluated traffic flow, that is, considering 1260 light vehicles and 150 heavy ICE vehicles, and gradually replacing the 1260 light ICE vehicles per light EVs (from 0% to 100%). When the flow of light vehicles is totally composed by EVs (100% of EVs), it could be reached a reduction of about 0.75 dB(A) in the noise levels emitted by the total flow. This reduction can be considered somewhat low, but here should be noted that the total traffic flow under evaluation is composed by a high proportion of heavy vehicles. Then, if the heavy ICE vehicles are not considered in the traffic flow, red line in Figure 1, the reduction becomes more relevant, achieving up to 2 dB(A).

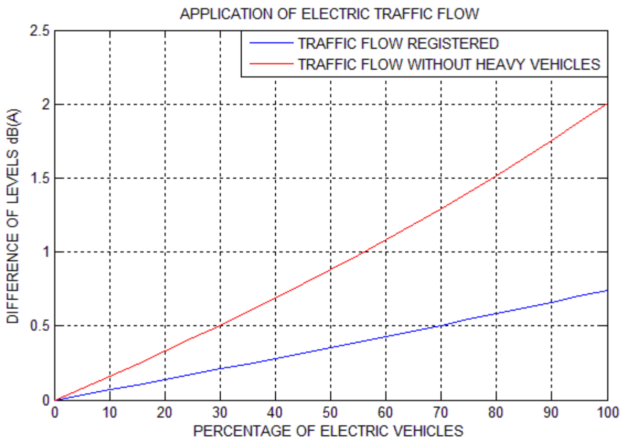


Figure 1 – Reduction of the noise levels in an urban environment due to the circulation of a EVs flow

Urban areas are composed by street intersections and different geometries which imply that urban traffic flow has not always a constant driving speed. In that sense, the French model considers three different driving conditions: constant, accelerating and decelerating speed. Then, taking into account such factor, the presence of EVs in urban flows could involve a higher reduction of the sound levels in those areas. In the Figure 2 it can be analyzed such effect. Here is represented a traffic flow composed by only light EVs, where the blue line shows the sound reduction, in dB(A), at different constant driving speeds. Here it can be observed the previous results for the 30km/h, where a reduction of 2 dB(A) were obtained. The red line represents the same traffic flow, but now driving on accelerating conditions. The reduction reached by a traffic flow totally composed by EVs driving on accelerating conditions, for instance at 30km/h, are about 8dB(A). That situation would imply a very drastic reduction in the urban noise levels, which would be even improved at lower speeds.

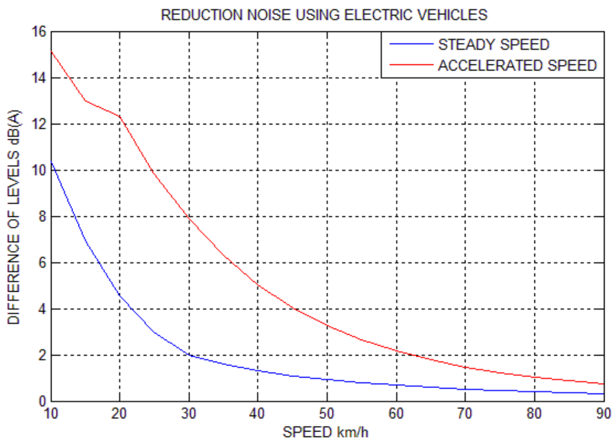


Figure 2 – Noise levels reduction depending on the driving conditions of a EVs flow

Finally, it was analyzed the effect of the EVs emission when these are equipped with AVAS systems. For that purpose, it was integrated in the updated traffic noise prediction model the optimal sound power level of a warning sound. According with previous studies found in the literature (34), it is estimated that increasing in 2 dB(A) the total sound pressure level of an EV driving at 20km/h, the detectability of the EV would be similar to the detectability of an ICE vehicle. Taking into account such hypothesis, the model was adapted to include the emission of AVAS systems, obtaining as a result the differences showed in Figure 3. Here it can be observed that the noise emitted by an EV with an AVAS system integrated, is lower than the emitted by an ICE traffic flow driving under the same conditions. The repercussion of EVs using warning sounds is lower than EVs without them, but they do not exceed the levels of ICE vehicles. In this case, the reduction is about 1 dB(A) if there are no heavy vehicles in the traffic flow.

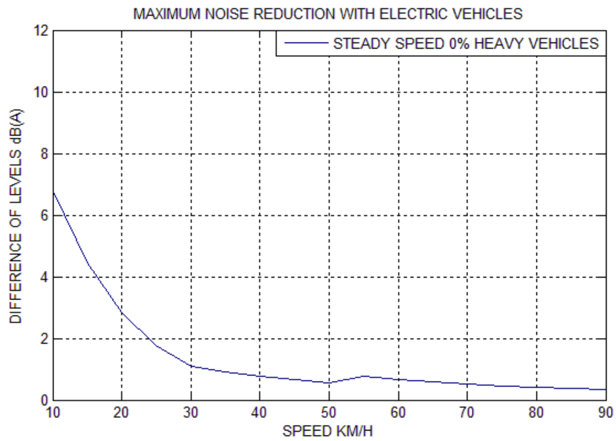


Figure 3 – Differences between 100% AVAS-EV vs 100% ICE vehicles traffic flows

#### 4.1.3 Results of EVs' influence on a Noise Map

In this section, it is presented an application example of the implementation of the updated traffic noise prediction model for the calculation of a noise map. The objective of this part of the study is to assess the inhabitants' exposure to environmental noise levels, comparing the results of a noise map with and without EVs. The urban noise map of an urban area of Elche (Spain) was simulated, in which the current traffic is composed by light ICE vehicles and heavy ICE vehicles, and where the limitation speed is 30km/h. Then, it was added the sound power levels emitted by the flow of EVs by means of the modification implemented to the French model. Finally, taking into consideration the real traffic on the studied area, it was evaluated the acoustical situation of 875 buildings, with 12232 inhabitants. Several methods exists for calculating the number of people exposed to noise in urban areas, and among them, the German National Method VBEB (35) was selected.

The Figure 4 shows the results the number of inhabitants exposed to the noise levels emitted by a traffic flow of all light ICE and heavy ICE vehicles (red bars) and to the noise levels emitted after substituting the light ICE vehicles by all EV vehicles (blue bars). The study has been developed considering the Spanish regulation (36), that restricts to 65dB(A) the maximum noise level permitted to be registered on a building façade. According to the results, if all light ICE vehicles in the area under study are substituted by EVs, would imply an increase of 10% of the number of citizens that would meet the sound quality objectives fixed by the Spanish legislation in the area under study.

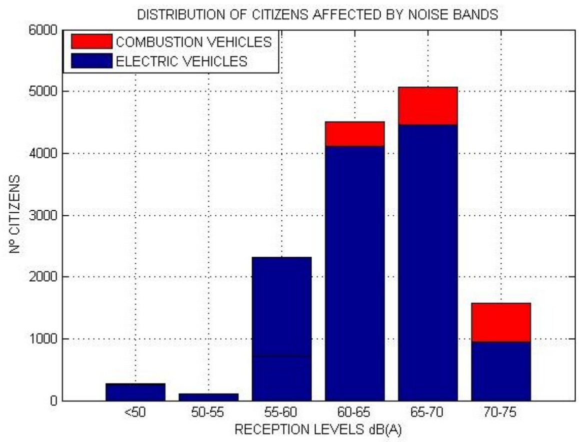


Figure 4 – Inhabitants exposure depending on the vehicles type

## 5. CONCLUSIONS

The COST Action TU1105 "NVH (noise, vibration and harshness) analysis techniques for design and optimization of hybrid and electric vehicles (H-EVs)" initiated its activities in April 2012, with the main objective of serving as an instrument for acquiring, unifying and coordinating necessary information about techniques for the analysis, design and optimization of hybrid (HVs) and electric vehicles (EVs). The Action has run during the last four years, in which it has become a large consortium composed by 34 institutions from 14 COST countries, plus 3 institutions from 3 non-COST countries, engaging a wide group of NVH experts from vehicle industries and research groups. During the Action lifetime, the consortium has achieved cutting-edge results, collected in a book where the challenges originating from the use of alternative powertrains, the customers' perception about the new generation of vehicles, the discussion of potential solution technologies and the definition of fields for future research are collected and discussed.

In this paper it is presented a brief review of the features posed by the alternative vehicles, and it is compiled some experimental and numerical techniques developed within the Action to face the NVH issues related to those vehicles. Besides, this paper also contains an analysis of the expected noise effects of the implementation of EVs in urban traffic flows by means of its results on the noise maps plots. The emergence of that new type of vehicles, lacking of engine noise, should improve the acoustic environmental conditions. It has been checked that in extra-urban speed, for driving speeds higher than 50 km/h, the benefits are low or worthless due to the dominant contribution of rolling noise. However, that situation improves for urban driving speeds, since it is estimated a reduction of 2 dB(A) of the sound pressure levels provided by a whole flow of EVs running at a constant speed of 30km/h. When considering the more common urban traffic conditions, that is, an intermittent and accelerating traffic flow due to the street intersections and urban geometries, the improvement is even better, since it could be expected a noise reduction of 8dB(A).

As commented before, the installation of AVAS improves considerably the detectability of EVs and HEVs. However, the emission of AVAS should be specifically designed and controlled, in order to not contribute again to increase the noise pollution. As seen in this paper, it is estimated a reduction of 1 dB(A) of the sound pressure levels provided by a whole flow of EVs running at a constant speed of 30km/h, when they are equipped with AVAS. In this regard, the directivity of the sound emission could play a crucial role and must be considered during the design phase of AVAS systems.

Therefore, and to conclude, green vehicles are considered to be a major enabler to reach the CO2 targets, but they are also expected to contribute to environmental noise reduction. According to the results presented in this paper an interesting percentage of citizens could improve their acoustical living situation by meeting the sound quality objectives fixed by national legislations. Hence, the integration of EVs and HEVs in urban fleets, together with combined governmental strategies (for instance, to implement lower speed limits in sensitive areas, the use of low noise road surfaces and a proper location for their installation, the development of silent tyres, etc), could help to improve the acoustical quality of citizens and the comfortable driving conditions of H-EV's users.

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