New Features on Noise, Vibration and Harshness Posed by the Next Generation of Vehicles

Nuria Campillo-Davo[a], Miguel Sanchez-Lozano[a], Ramon Peral-Orts[a], Bert Pluymers[b] and Wim Desmet[b]

[a]Department of Mechanical Engineering and Energy
Miguel Hernandez University
03202, Elche, Alicante, SPAIN

[b]Noise and Vibration Research Group
Department of Mechanical Engineering
KU Leuven, BE-3001, Heverlee, BELGIUM

ABSTRACT

Traffic noise is generally considered one of the most important sources of environmental pollution in urban and interurban areas. Each individual vehicle in the traffic flow contributes to the total emission by means of three different sub-sources: noise emitted by engine, exhaust and transmission; aerodynamic noise; and noise radiated during tire/road interaction. Those sub-sources play a different role depending on the characteristics of the traffic, i.e. for low speed traffic – less than 30km/h – mechanical noise coming from engine and drive chain is the prominent, whilst for high speed – above 30km/h – the main contribution is related to tire/road noise. The new generation of hybrid and electric vehicles (HEVs) will contribute to a reduction of noise pollution through reduced use or inexistence of the internal combustion engine. That feature, which is positive for environmental noise control, carries a negative connotation since low noise emissions of HEVs represent an actual danger to pedestrians. Also drivers of HEVs should adapt their driving style and behavior to the new features related to noise, vibration and harshness (NVH) inside the cabin. In order to solve that problem, warning sounds are being designed by HEVs manufacturers, but, it is not actually known how those new sounds will integrate into urban soundscapes. These and many other questions arise related to the increased presence of electric vehicles in city car fleets. The Research Group in Applied Mechanical Engineering of Miguel Hernandez University in Spain is currently coordinating the COST TU1105 Action “NVH analysis techniques for design and optimization of hybrid and electric vehicles”, together with the Noise and Vibration Research Group of KU Leuven in Belgium. The aim of the Action is to engage NVH experts from vehicle industry and renowned research groups in the accumulation, development and dissemination of novel analysis techniques to be developed for the next generation of vehicles and their drivers. In this article, new features posed by HEVs are discussed and latest developments on the topic are presented.

Keywords: Electric and Hybrid Vehicles, Noise, Vibration, Driver and Pedestrian Safety

INTRODUCTION

Hybrid Vehicles will play a major role for long time, well beyond 2030. They are a major enabler to reach the CO2 targets, to reduce gas emission in general, to enable good air quality in urban areas and to spare the non-renewable

https://openaccess.cms-conferences.org/#/publications/book/978-1-4951-2098-5

energy resources. Since Hybrid Electric Vehicles (HEVs) do not have the range limitations of Full Electric Vehicles (FEVs, further referred to as Electric Vehicles – EVs) and also not the drawback of emissions like the pure Internal Combustion Engine (ICE) vehicles, they are more in line with the consumer's needs and the driving patterns of today and of tomorrow. HEVs combine the advantage of two different propulsion systems, the possibility to drive with zero emission and to drive on long distances. EVs will dominate as pure city- and short distance solutions. Hybrids will be the major solution for sustainable mobility, for individual mobility, for goods transport and for public transport, suitable to enter cities as well.

Worldwide demand for HEVs will advance rapidly from 1.6 million units in 2010 to 4.3 in 2015 to nearly double that number by 2020 (The Freedonia Group, 2006). Currently, HEVs have become already an established solution in the US market. The Asia Pacific region, however, remains the hotbed of activity where a major portion of demand stems from Japan. HEVs and EVs are seeing widespread adoption in Europe too, where environmental consciousness has strongly increased over the last decade and strict adherence to EU environmental directives and Copenhagen Protocol requirements has become a requisite. In this context there is an increasing awareness around the issue of the environmental noise. The World Health Organisation is reporting that traffic noise causes every year the loss of at least one million healthy life-years in Europe and responsible for over 20.000 deaths each year via resulting heart problems, reduced sleep quality, etc. The road industry alone cannot entirely solve this problem: road users, public authorities, automotive constructors have their role to play as well. Therefore real and tangible effects in noise reduction could only be achieved by a common effort and a shared responsibility of all these actors.
On the other hand the very low noise levels due to an approaching electric or hybrid car can be a danger to pedestrians and cyclists. Of particular concern are small children and the elderly. Hybrids may generate a sufficient noise level to warn pedestrians under some driving conditions, but then suddenly reduce their level under other conditions, particularly as they slowdown in circumstances where they are more likely to be mixing with pedestrian traffic. Several manufacturers have developed external noise generators for such vehicles but there remain two outstanding issues. First, how a significant warning level can be generated in front of the vehicle, without generating significant environmental noise pollution by radiating high noise levels from the sides and rear of the vehicle. The second issue is concerned with the best character of the warning noise to use. This should be perceived to be coming from a vehicle but not as alarming that it will cause a startle reaction and thus increase the danger.

Concerning the vehicle interior aspects, a relevant current trend is the active control of the overall sound quality in a vehicle, rather than just the sound level. This may become important with the use of hybrid vehicles and vehicles with variable cylinder management, since the changes in the quality of the sound inside these vehicles, as well as the power source changing character can be disconcerting to the driver. The active control of sound quality generally involves a control system that drives the microphone signals inside the car towards a target, or command, signal, rather than just minimizing it. This has been termed "noise equalization", "sound synthesis", "active design" and "sound profiling" and can include the use of psychoacoustic models. Recent trends also include the use of active control systems to provide a smoothly changing sound profile with engine speed, but with an emphasis on sporty sound during acceleration, to make the vehicle "fun to drive". Further development along these lines is also possible by providing an acoustic environment inside the vehicle that encourages the owner to drive in a more fuel-efficient way, for example. There has been some resistance to this trend towards of active control of sound quality in some parts of the automotive industry, where such electronic sound control is seen as 'cheating' compared to mechanical re-design. However, as more virtual systems are introduced in vehicles with active braking, stability and steering, and with a younger generation of customers, more used to audio manipulation, these objections are likely to die away.

Given the above NVH issues and the continuous development of next generation HEV and EV powertrains, whereas the currently released vehicles are still more or less prototyped systems build on existing vehicle platforms, the main objective of the TU1105 COST Action "NVH analysis techniques for design and optimization of hybrid and electric vehicles" (TU1105 COST Action website) is to acquire, unify and coordinate necessary information about vehicle dynamics, driveability and noise, vibration & harshness (NVH) analysis technologies in view of the challenges posed by the novel power train concepts (with HEV and EV including all types: series, split and parallel hybrid vehicles and range-extended). The main mean to achieve this objective is the generation of a network in order to form a critical mass of expertise. Although in the past a lot of research effort has been spent on the development of NVH analysis tools, these existing tools are mainly applied to conventional IC vehicles and the limited knowledge on electric and hybrid vehicles is scattered all over Europe. In order to identify shortcomings in current state-of-the-use and to pinpoint areas in which new technologies need to be developed, a review of the existing technologies has to be made. In such a way knowledge fragmentation can be reduced and the efficiency in developing novel methods dedicated to EV and HEV will be increased. TU1105 will provide the necessary coordination in order to set up the development of these novel methods.

This paper reports on the progress of the Action going into its third project year, summarizing the results obtained so far and the work planned for the second period of two years.

THE TU1105 COST ACTION

The TU1105 COST Action "NVH analysis techniques for design and optimization of hybrid and electric vehicles" is hosted in the intergovernmental framework for European Cooperation in Science and Technology (COST). The network started in April 2012 with 13 representatives from 8 countries, and nowadays it is composed by 36 entities from 15 countries (including 2 Non-COST Countries: New Zealand and Brazil) coming from the academia and also the industry. The consortium promotes the transfer of knowledge by means of meetings, training schools, short term scientific missions and dissemination of results at conferences and publications.

The main objective of the Action will be achieved by accomplishing a set of secondary objectives. In this respect, it will be necessary to analyse the current situation and the state-of-art, and to promote the networking among the partners, in order to bring together fragmented NVH knowledge and to adapt NVH technologies from ICE to EV and HEV when possible. It is also essential to collect customer's perception by means of questionnaires and to assess industrial requirements now and over the time, as these groups will be some of the end-users of the Action. Also, it will be required to stimulate users, transport companies and authorities responsible for the development of infrastructures about new existing interactions between EV/EV and the environment, and to bootstrap on existing and stimulate and seed new European initiatives in the field. Finally, the network will disseminate NVH research results towards likely end-users.

The scientific program of the TU1105 COST Action is structured into five Work Groups, which activities are focused on achieving the objectives stated above: WG1: state-of-the-art concerning NVH techniques on ICE vehicles and NVH characteristics of novel HEVs and EVs vehicles; WG2: development of experimental NVH analysis techniques; WG3: development of numerical NVH analysis techniques; WG4: development of sound quality metrics and sound engineering of HEVs and EVs, including safety aspects; WG5: transfer of the knowledge to likely end-users.

In the next chapter are explained the main areas of research and activity within the network that nowadays are being developed. These correspond to the activities within WG2, WG3 and WG4. The activities within WG1 have been already finalized and nowadays WG2 is the responsible of interpreting the data about customers' expectations. Finally, activities related to WG5 will be performed at the end of the Action lifetime.

AREAS OF WORK WITHIN THE TU1105 ACTION

Experimental NVH Analysis Techniques

The main objectives of NVH experimental techniques are to determine the characteristics of the noise and vibration sources, as well as the transmission paths to driver and passengers. In fact, the absence of ICE engines and other mechanical noise issues, change the relative importance of the other noise sources of the EV, so, that is one of the reasons why the identification of noise sources in an EV is so important to assess the interior sound comfort. In effect, although electric vehicles are significantly quieter, their interior noise is marked by high-frequency noise components which can be subjectively perceived as annoying. At the same time, the lack of external noise supposes a real danger for pedestrian, been necessary to use warning sounds that improve saving conditions without affecting interior sound comfort and exterior noise pollution.

Previous characterization of EV's justifies the importance of experimental techniques to analyze and identify NVH sources of Electric Vehicles. Some of the traditional tools are well-know devices to study ICE vehicles and to solve vibro-acoustics issues, it is the case of:

- Order tracking
- Modal analysis
- Noise mapping techniques such as sound intensity
- Near-field acoustic holographic and beamforming

But some of them will not be useful for experimental NVH analysis of the EV's due to the fact that they target towards the mechanical engine of the vehicle, so they are being currently adapted to the electric vehicle conditions (Finger et al., 2012).

Interior NVH Techniques

A useful technique to study NVH of an EV is the Transfer Path Analysis (TPA) (Sarrazin et al., 2014). TPA models the connection between a noise source and one or more receivers (see Figure 1). The TPA method identifies the amount of excitation by measuring excitation force by introducing a force sensor (matrix and stiffness methods are estimative alternatives).

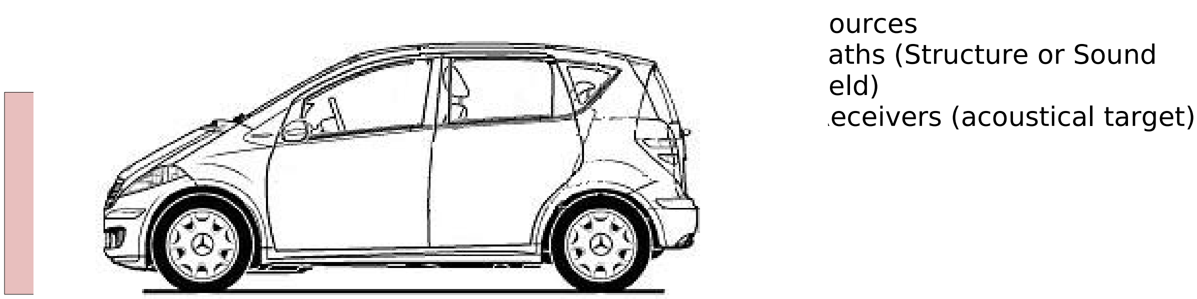

Figure 1. Transfer Path Analysis identifies the effect of NVH source to the potential receivers

Based on experimental dates, a variety of signal processing methods including statistical analysis, spectral analysis, time-frequency analysis and wavelet transform have been also used to separate close occurrences and analyze EV's sources noise and vibration.

Source identification techniques like sound intensity, acoustic beam-forming and acoustic holography are used for a number of reasons outside of troubleshooting including calculating sound power, deriving acoustic impedance, estimating sound radiation and calculating surface velocities for acoustic modelling support. But the primary purpose of noise source identification is to locate where the majority of the noise comes from, being of particular interest in a complex acoustic environment. The location of the source with these techniques is also useful in small electromechanical devices that operate with a cover, where the source is difficult to separate. Batteries with integrated pumps and cooling fans and small gear trains are examples of products where localizing the noise source would be very difficult without these techniques.

Structural Techniques are also used to understand the structure enough to make a design modification. The main methods used to describe the structure motions are operating deflection shapes (ODS) and experimental modal analysis (EMA). ODS can be performed as time, frequency spectra, or be RPM based. EMA is performed with hammer or shaker input. The goal of ODS is to determine the real-world forced deflection during operation through measuring transmissibility between a reference transducer and a group of roving response transducers. On the other hand, the objective of modal analysis is the construction of a mathematical model of the inherent dynamic properties and behavior of the structure through measuring the frequency response function between a force transducer at a driving point and group of roving response transducers (Park and Lee, 2014).

Exterior NVH Techniques

Electric vehicles at low speed are extremely quiet, because of the lack of tire/road noise. Pedestrians use auditory as

https://openaccess.cms-conferences.org/#/publications/book/978-1-4951-2098-5

well as visual cues as warning signals that a vehicle is approaching. Current regulatory requirements aim at limiting the noise emitted by a vehicle in its loudest mode of operation (see pass-by test in ISO 362), and there is still no provision for ensuring that quiet vehicles can be heard by pedestrians.

Some research groups are currently developing sound generator systems, and they are using experimental techniques to evaluate the behavior of the proposed systems and how they are going to affect to the vehicle perception and to the environment.

Other sources are studied using traditional experimental techniques such a pass-by test, drum tests or coast-by test, but alternative methodologies could be able to identify moving noise sources (Peral et al., 2010), the horizontal directivity of EV's or the power level tire/road noise (Campillo-Davo et al., 2013).

Numerical NVH Analysis Techniques

Working Group 3 focuses on the development of numerical NVH analysis techniques. Numerical methods are very powerful in accurately modeling and predicting vibration and sound radiation from complex structures. The most widely used numerical methods are the Finite Element Method (FEM) and the Boundary Element Method (BEM). Both of them can be used for structural and acoustic analysis but due to certain advantages and disadvantages FEM is mainly used for structural problems whereas BEM is used for acoustical problems. These methods, together with others as multi-body or lumped simplified approaches, have been used extensively in the detailed design of vehicles to achieve optimum designs. The catalogue of commercial software for performing FEM, BEM or multi-body analyses has become very wide.

But electric and hybrid vehicles are characterized by different noise and vibration behavior. In addition, these vehicles can present simplified or unusual driveline configurations, and different vehicle architectures can be found. And finally, some new materials are being used in EV, with different behaviors from the traditional ones used in conventional vehicles equipped with internal combustion engines.

As a consequence, some of the existing numerical methods for NVH analysis may be invalid for those unusual operating conditions, and techniques may need to be adapted. In most cases, the existing methods should be valid, but the results to obtain (frequencies, intensities, etc.) will be in a range of values very different from the usual for ICE vehicles.

According to the Memorandum of Understanding of the Action, the deliverables obtained by this Working Group should be:

- Definition and development of numerical NVH analysis techniques to determine the modes, the characteristic frequencies and the relevant non linear effects of the driveline.
- Definition and development of numerical techniques to simulate the dynamic behavior of new materials used in electric vehicles.
- Integration of simulation and experimental measurements.

To accomplish those targets, a comparison of existing numerical methods will be made for some EV and component examples, and their utility will be verified compared to ICE. The study could cover finite elements models, boundary elements models, multibody and lumped mass models. The different research groups involved will share their methodologies for modeling, and experimental measurements realized by partners acting in WG2 will be used for validation of models.

The comparison between the numerical simulation methodologies will be based on several common benchmarks, with different levels of complexity. For example: one detailed transmission component model, one driveline subsystem model, one entire vehicle model, etc.

Depending on the complexity, models could include the following items:

- Electric machine models

https://openaccess.cms-conferences.org/#/publications/book/978-1-4951-2098-5

- Gear noise and vibrations models
- Tire/road noise models
- Aerodynamic noise models
- Various damping material model for noise / vibration attenuation
- Interior noise propagation models
- Exterior noise propagation models

As a result of WG3 activities, a comparison of the utility and scope of various numerical methods will be obtained, and particulars of their application to the NVH analysis of electric and hybrid vehicles will be discussed. Some conclusions could also be obtained related to general results expected for EV noise and vibration, and sensitivity to different parameters and conditions.

Sound Quality Metrics for User's Perception

The noise signature of a traditional ICE vehicle presents quite differences from the noise footprint of an EV. As commented previously, beyond the reduction of noise provided by the electric engine, some other systems become more relevant in acoustical terms, as now those sources are not masked by the noise of the combustion engine. Such is the case of the whining noise coming from the gearbox, or the tire/road noise and wind noise. Also new sources appear, as possible high frequency tonal electric motor noise and the noise generated by complex transmission systems. Finally, warning sounds to increase pedestrians' safety are being developed to be implemented in EVs.

The features exposed above will condition the response of drivers and pedestrians facing an EV, both in terms of interacting with the vehicle and also the level of accomplishment reached related to the customers' expectations. The development and validation of sound quality metrics will allow to indicate which experimental and numerical techniques can give the best understanding of the NVH issues of EVs.

Regarding to the sound quality in the interior of the cabin, some studies on sound quality metrics applied to H-EVs sounds are found in the literature (Szatkowski, 2013). Those metrics can be improved by means of listening experiments using measured and modified interior noise recordings, in both conditions: stationary constant speed and acceleration. The comparison of both metrics results shall permit to propose a series of guidelines to ensure a high sound quality inside the cabin of an EV.

Concerning the exterior vehicle noise, and specifically in relation to warning sounds, previous work can also be found in the literature, for instance the eVADER project (eVADER Project) where it was analyzed the timbre features on detectability of EVs. However, further work must be developed such as a comparison between existing sounds and those recommended for instance by European regulations.

CONCLUSIONS

The TU1105 COST Action is running until April 2016 and the expected potential impacts will be based on achieving a uniform point of view of the new features on NVH posed by the H-EVs. In this sense, the completion of the Action will imply to obtain a clear understanding of NVH features of H-EVs and of involved subsystems, which will allow to propose the standardization of test rigs and experimental procedures to quantify external/internal H-EVs noise. Besides, the development of dedicated analysis numerical and experimental tools for H-EV NVH analysis will provide a collection of best practices for the research on this field. Finally, the development of common NVH metrics, in the form of guidelines, to characterize noise annoyance acceptance, will enable to analyze the customers' expectations taking into consideration the ongoing changes on the NVH features that may occur thanks to further research and innovation in the field of EVs.

The end-users of the Action are all those people concerned in the field of NHV of EVs, as experienced and earlystage researchers, European authorities for transport regulations, independent consultants, experienced representatives from industry and relevant associations. But also vehicle customers, pedestrians, cyclists, and indirectly the whole European society will benefit of the Action achievements.

REFERENCES

Campillo-Davo, N. Peral-Orts, R. Velasco-Sanchez, E. Campello-Vicente, H. (2013). "An experimental procedure to obtain sound power level of tyre/road noise under Coast-By conditions". Applied Acoustics 05/2013; 74(5):718–727.

eVADER Project. http://www.evader-project.eu/

Finger, K. Brandes, M. Schmidt, E. (2012). "TPA and NVH Prognosis – Application to Mercedes Benz Car Development of New Hybrid Methods Coupling Digital Simulation with Prototype Testing Results". SAE International Journal of Passenger Cars - Mechanical Systems. 5(3):1091-1100, 2012.

Park, J. Lee, H. (2014). "Study on the Vehicle Cabin Noise Employing the Interfacial Friction in Double Layered Frames Used in Electric Vehicle Traction Motors". SAE International Journal of Passenger Cars – Electronic and Electrical Systems. 7(1):2014.

Peral-Orts, R. Velasco-Sanchez, E. Campillo-Davo, N. Campello-Vicente, H. (2010). "Noise source detection system based on two independent microphone arrays". INTERNOISE 2010. Lisbon, June 2010.

Sarrazin, M.M. et al. (2014). "Electro-Vibro-Acoustic Analysis of Electric Powertrain Systems". FISITA 2014 World Automotive Congress.

Szatkowski, A. (2013). "Passenger Vehicle Hybrid Hydraulic Powertrain Sound Quality Investigation". SAE Technical Paper 2013-01-2004, 2013.

The Freedonia Group. (2006). "World Hybrid-Electric Vehicle", Oct. 2006.

TU1105 COST Action. http://www.tu1105.ulg.ac.be/index.html