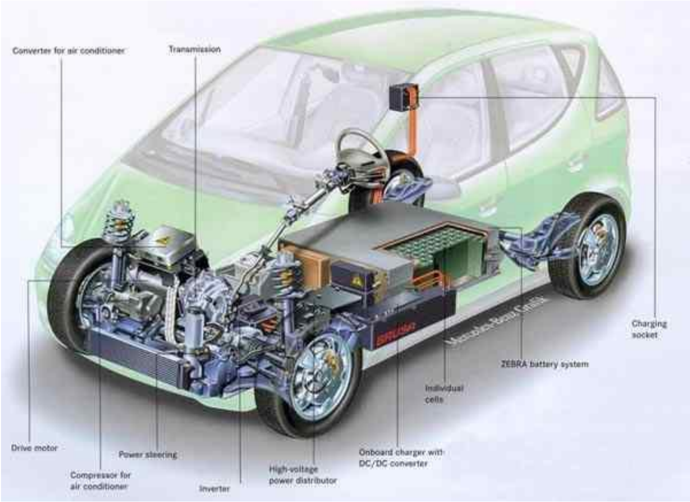
COST Action TUD 1105
Year 1
WG1 task

NVH analysis techniques for design and optimization of hybrid and electric vehicles

Extended Scientific Report

State of art in NVH of ICE and Electrified Vehicles



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1. NVH in automotive

Reducing the amount of sound radiated by machines has become a main concern over the last decades. This is mainly because societies are becoming more aware of the impact that prolonged **exposure to noise** has to human health. As a result standards and regulations regarding noise are becoming more and more strict. Another aspect concerning the noise is that it is one of the **fastest growing pollutants** in Europe'[1]. The contribution due to the increase of traffic is dominant.

All these aspects sometimes conflicts with the **vibration comfort** that significantly effects the customer decisions and thus presents a key feature in the competitive success of European vehicles compared to those from other continents.

Noise, Vibration & Harshness (NVH) describes the dynamic behaviour of vehicles in the whole frequency range. It comprises the sensible low frequency vibrations of structures, the sensible and audible range of perceived acoustical comfort (Harshness), as well as the audible high frequency range of noise limited by the perception ability of the human ear. A common methodology of dealing with noise and vibrations in cars and other complex machineries is adopting a system analysis approach. In this, one or more excitations produce one or more responses through the **transfer function** of the system. In vehicles, the **excitations** are all the possible noise and vibration sources (or Noise Generation Mechanisms, NGM) such as engine vibrations, exhaust system acoustic radiation, etc. Usually, engineers are interested in the response of these sources at certain points inside the car compartment, such as driver's and/or passengers' ears locations. Hence, the transfer function in the system approach is the transfer function from the noise or vibration source to the **receiver** and this can be **vibrational, acoustic or a combination of both**.

In cases of many noise and vibration sources a cascade approach is usually used to categorise them. A basic distinction of noise sources is structure-borne and air-borne sources. For the case of vehicle NVH **structure-borne noise** sources include engine vibrations, vibration due to tyre/road interaction, vibrations of the exhaust, etc. **Air-borne** sources include acoustic radiation from the engine block, aerodynamic noise, exhaust and intake noise, etc. An alternative to this is to consider all possible sources at the first level of the cascade model and at the second level to consider the transmission paths that the sources follow, categorised as **acoustic and structural paths** [2][3] (Figure 1). The cascade analysis can help in the development process described above. At the first stage, targets can be set for each individual noise path. In the detailed design stage these paths can be studied individually and different designs can be implemented to achieve the targets. In the prototyping stage a design can be verified experimentally.

A very powerful tool that has been extensively used in the automotive industry for the analysis of different noise paths is the so called **Noise (or Transfer) Path Analysis (NPA or TPA)**[4]. Using this, the transfer functions of the paths that have been defined in the cascade model can be measured. Also operational data of all different sources can be determined. Hence, a complete description of noise

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[1] European Commission's Green Paper of 4th November 1996 on *Future Noise Policy* /*COM/96/540 FINAL*/

[2] Rousounelos, A. *Reduction of Sound Radiation from Automotive-Type Panels*, Doctoral Thesis Loughborough University, 2010

[3] P. Saha, *Developing Vehicle Sound Packages*, Sound and Vibration, October 2011

[4] P. Van de Ponseele, H. Van der Auweraer, K. Janssens, *Source-Transfer-Receiver approaches: a review of methods*, Proceedings of ISMA2012, Leuven, Belgium, Pages 3645 - 3658

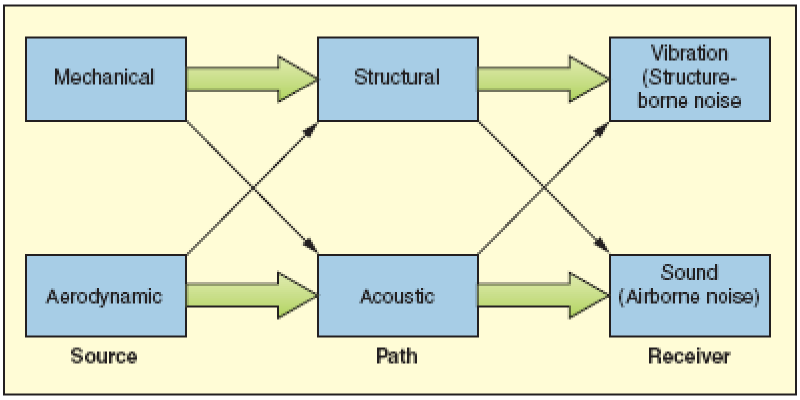

Figure 1 - Vehicle noise mechanism

characteristics of a vehicle can be achieved with a good insight into its causes. Moreover, for a more detailed description of a noise path, it can be subdivided into different components.

For example, for noise generated by the engine vibrations as it is heard by the driver, the path consists of the car body and the acoustic cavity in the car compartment. The structural path (car body) can be subdivided into different panels, such as dash board, roof panel, floor panels, etc. The contribution of each panel to the sound pressure at the driver's location can then be determined by performing a panel contribution analysis.

From the above discussion it is clear that in order to minimise noise to achieve predefined targets for a vehicle, one needs to either modify the noise generated by different sources (or the way these are coupled to the vehicle structure) if possible, or modify the paths that noise follows.

Methods for the study of vibro-acoustic problems can be categorised into **analytical, numerical and experimental** methods. The advantages of **analytical methods** are that they can predict acoustic and/or vibration results without many computations required in a short time and usually without frequency limitations. They can also shed light to physical mechanisms involved in certain phenomena. The main disadvantage of analytical methods is that they can be used only for simple problems (e.g. simple structures). Analytical methods can be used to quickly compare different design alternatives without the need for considerable analysis effort, by roughly seeing how different parameters influence quantities such as radiated sound pressure or sound power. This can be very useful in the conceptual stage.

Numerical methods are very powerful in accurately modeling real life situations. They can be used to predict 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. In contrast with analytical methods, numerical methods require a great number of computations and usually take a long time to be performed. Moreover, they need considerable manual effort to design detailed models. They are also only applicable for low-frequency analysis. Numerical methods are used extensively in the detailed design stage. Many commercial computer software can perform FEM and BEM analyses. For the purpose of minimisation of sound radiation by structures, numerical methods have been used in conjunction with numerical optimisation algorithms to achieve optimum designs.

On the other hand many **experimental tools**[5] [6] are at the engineer's disposal to solve vibro-acoustics issues: order tracking; modal analysis; noise mapping techniques such as sound intensity; near-field acoustic holographic and beamforming; and several others[7]. Order tracking is an important troubleshooting tool to use for identifying the source and characterizing the paths as well as for better description of the receiver. To understand the structure enough to make a design modification, it is often necessary to define the motion of the structure during an objectionable event. The two methods used to describe these motions are **operating deflection shapes** (**ODS**) and **experimental modal analysis** (**EMA**) 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. Moreover, there are a variety of noise source identification techniques available today including sound intensity, acoustic beam-forming and acoustic holography. These techniques 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 modeling support.

Finally, as alrady mentioned, the TPA method identifies the amount of excitation (source) going into a particular path and combines that with the sensitivity of that path to calculate a partial noise and/or vibration calculation.

Noise and vibration play an important role in what is called the **sound quality** of the vehicle[8]. Vehicle sound and vibration quality is a very broad subject,since our interaction with the vehicle is fairly complex. Audio and tactile feedbacks are combined with visual cues and ever-changing driving and boundary conditions. In industrialized societies, where the use of passenger cars has been prevalent for the last several decades, we have developed precise expectations for the **"feel" of a car**, and these expectations drive, along with **cost** and **fuel consumption**, the purchasing decisions. Automotive companies around the world have invested considerable resources in the past 20 years to understand what role sound and vibration play in a **customers' perceptions** and to establish **realistic targets** to ensure commercial appeal.

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[5] Janssens K., Vecchio A., Van der Auweraer H., *Automatic Extraction of noise annoyance features from vehicle run-up sounds*, Proceedings of ISMA 2006

[6] John and Phillip Van Baren, I*mproving random vibration tests for the Transportation Industry*, Sound and Vibration, September 2012

[7] G. Cerrato and P. Goodes, *Practical Approaches to Solving Noise and Vibration Problems*, Sound and Vibration, April 2011

[8] G.Eisele, G.Cerrato, Automotive Sound Quality – *Powertrain, Road and Wind Noise, Sound and Vibration*, April 2009, Pages 16-24

2. NVH in ICE Vehicles

a. Introduction

This part deals with the analysis of the main vibroacoustic problems related to the **NVH of conventional ICE engines**. An overview of the noise sources and paths for interior noise, followed by a description of the **experimental techniques** currently applied to reduce interior noise, is presented. Morevoer a short description of the available **simulation tools** is given.

b. IC vehicle sources of noise and identification techniques

There are many sources of noise in a IC vehicle: in the past the engine was the most important, and the first NVH studies were applied to reduce noise and vibrations generated by the **engine** and **powertrain**. As a result current engines and powertrain systems show a strongly reduced level of noise, and consequently other sources of noise such as **road** noise become very significant. Moreover, the increase of the speed of vehicles has strongly increased the importance of **aerodynamic noise**. Below is a literature review concerning the main noise sources in ICE vehicles[9].

The noise from a **ICE engine** is composed of many components emitted from different sources, see Figure 2. These sources include **combustion noise**, **mechanical noise**, and a **combination of both**[10] [11]. Table 1 briefly summarises **ICE engine noise excitation forces**, their generation mechanisms and noise transmission paths. Especially in **diesel engines** the **combustion noise** is produced by the rapid rate of increase of cylinder pressure, which besides being a source of engine structural vibrations also excites resonances in the gas inside the combustion chamber cavity.

Li et al.[12] confirm that the most fundamental source in **diesel engines** is the combustion-induced noise. It occurs towards the end of the compression stroke and subsequent expansion stroke. The rapid pressure change due to the combustion transmits through engine structures and forms a part of the airborne noise. This pressure change also causes the vibration of the engine components such as the cylinder head, pistons, connecting rods and engine body. The vibration of these components then provides another part of the overall engine noise. Together these noise sources account for over 80% of total engine noise. The combustion-induced noise is however the dominant source. Other noise sources are due to engine functions such as **the injection of fuel** and **the operation of inlet and exhaust valves**. These sources usually produce low level noise and make up a fraction of the overall noise. The transfer function of engine's combustion noise can be obtained through experimental method by Ge-qun[13].

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[9] D. Vigé, *Vehicle interior noise refinement – cabin sound package design and development* in Vehicle noise and vibration refinement Book, edited by Woodhead Publishing Limited, 2010

[10] Albarbar, F. Gu, A.D. Ball, A. Starr *Acoustic monitoring of engine fuel injection based on adaptive filtering techniques* Applied Acoustics, Volume 71, Issue 12, December 2010, Pages 1132-1141

[11] Waters, Lalor, Priede, *The Diesel Engine as a source of commercial vehicle noise*, Proc Instn Mech Engrs 1969-70, Vol. 134

[12] W. Li et al., *A study of the noise from diesel engines using the Independent Component Analysis*, Mechanical Systems and Signal Processing, Volume 15, Issue 6, November 2001, Pages 1165-1184

[13] Shu Ge-qun, Wei Hai-qiao and Han Rui, *The Transfer Function of Combustion Noise in DI-Diesel Engine* Proceedings of SAE, 2005-01-2486

The combustion and intake noise are also analyzed in detail by Kamiński[14] and Ih et at.[15]. Kamiński applies the *nonlinear multidimensional methods* which can distinguish random variations from a deterministic behavior for internal pressure signals. Ih predicts *insertion loss* (IL) and *radiated sound pressure level* (SPL) of the automotive for the fixed rpm and engine run-up condition. It was suggested that, for the purpose of approximate calculation of the overall trend of IL or radiated SPL of the intake system, anechoic source model and measured source impedance together with a cold engine condition could be good solutions.

Although the above engine mechanical and combustion noise sources have distinctive time instances, it is still difficult to resolve them accurately based on noise measurement. This is because the occurrences of each noise source are too close together.

A variety of **signal processing methods** including statistical analysis, spectral analysis, time-frequency analysis and wavelet transform have been used to separate close occurences and analyse engine noise and vibration. In particular *conditioned spectra analysis* and *virtual source analysis* can be applied to uderstand the noise generation and separate the combustion noise from the whole noise generated by an engine[16] [17] [18] [19] [20] [21].

Signal processing tools can be used also to detect anomalies generating noise and to improve the engine vibration source separation within the engine kinematics. In particular a methodology that combines *cyclostationary modelling* of the vibration signals in parallel with their angular sampling has been proven as useful for condition monitoring of IC engines[22] [23] [24]. Several indicators[25] [26] can be designed in order to detect a wide range of assembly and combustion faults during hot and cold test operations.

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[14] T. Kamiński, M. Wendeker, K. Urbanowicz, and G. Litak, *Combustion process in a spark ignition engine: Dynamics and noise level estimation,* Chaos 14, 461 (2004)

[15] Jeong-Guon Ih, Hoi-Jeon Kim, Seong-Hyun Lee, K. Shinoda, *Prediction of intake noise of an automotive engine in run-up condition* Applied Acoustics, Volume 70, Issue 2, February 2009, Pages 347-355

[16] Chung, J.; Crocker, M. & Hamilton, J. (1975), '*Measurement of frequency responses and the multiple coherence function of the noise-generation system of a Diesel engine*', Journal of the Acoustical Society of America 58(3), 635-642

[17] Alfredson, R. (1977), '*The partial coherence technique for source identification on a Diesel engine*', Journal of Sound and Vibration 55(4), 487--494

[18] Albright, M. (1995), '*Conditioned source analysis, a technique for multiple input system identification with application to combustion energy separation in piston engines*', S.A.E. Technical paper series(951376)

[19] Wang, M. & Crocker, M. (1983), '*On the application of coherence techniques for source identification in a multiple noise source environment'*, Journal of the Acoustical Society of America 74(3), 861-872

[20] Leclere, Q.; Pezerat, C.; Laulagnet, B. & Polac, L. (2005), '*Application of multi-channel spectral analysis to identify the source of a noise amplitude modulation in a diesel engine operating at idl*e', Applied Acoustics 66, 779-798

[21] Hayward, M.; Bolton, S. & Davies, P. (2012), *Connecting the singular values of an input cross-spectral density matrix to noise sources in a diesel engine*, in 'proceedings of Inter Noise 2012'

[22] Antoni, J., Daniere, J., Guillet, F., *Effective vibration analysis of IC engines using cyclostationarity. Part I - A methodology for condition monitoring*, , 2002, Journal of Sound and Vibration 257 (5) , pp. 815-837

[23] S. Delvecchio, G. D'Elia, G. Dalpiaz, *Comparing Wigner Ville Distribution and Wavelet Transform for the vibration diagnosis of assembly faults in diesel engines,* in Proceedings of the 21th International Congress & Exhibition on Condition Monitoring and Diagnostic Engineering Management 2008, Prague, Czech Republic, 2008 June 11-13, pp. 125-134

[24] S. Delvecchio, G. D'Elia, M. Cavallari, G. Dalpiaz, *Use of the cyclostationary modelling for the diagnosis of assembly faults in i.c. engine cold tests,* in P. Sas, B. Bergen editors Proceedings of ISMA2008 International Conference on Noise and Vibration Engineering, Leuven, Belgium, 2008 September 15-17, pp. 3191-3204

[25] S. Delvecchio, G. D'Elia, R. Di Gregorio, G. Dalpiaz, *On the monitoring and diagnosis of assembly faults in diesel engines: a case study,* in Proceedings of the ASME 2009 International Design Engineering Technical Conferences &

Blind Source Separation techniques have been employed to separate the combustion noise from pistoln slap. Different methods could be found in letterature. By using *blind least mean square* (BLMS) algorithm it has been proven that the recovered pressure shows that the part due to combustion and the part due to piston movement are two separate sources of different character. The combustion pressure part is shown to be super-Gaussian with high frequency and causes much more noise than the second part[27]. The *deflation metod*[28] and *spectrofilter*[29] are also used to improve the separation[30] [31].

Acoustic imaging[32] [33]technologies have seen constant development over the past decades. Two main approaches must be distinguished: the *beamforming technique*, and the *near field acoustical holography (NAH) technique*. The basic principle of beamforming is processing microphone signals with adequate time delays in order to obtain constructive interferences for acoustic waves coming from one particular direction. The main advantage of beamforming is the robustness of the method, while the drawbacks are its resolution limitations at low frequency, and its qualitative-only assessment of acoustic source strengths. NAH, contrary to beamforming, is based on acoustic measurements in the near field of the studied source. This method, more sophisticated than beamforming, is based on a numerical treatment of the acoustic pressures recorded by microphones, allowing one to retro-propagate the acoustic waves from the measurement surface to the source surface.

Within the framework of acoustic imaging, *Cyclic sound intensity*[34] is a rich concept with several original ramifications. Among other things, it returns a unique decomposition into instantaneous active and reactive parts. Associated to acoustical imaging techniques, it allows the construction of sound radiation movies that evolve within the engine cycle and whose each frame is a sound intensity map calculated at a specific time – or crankshaft angle – in the engine cycle. This enables the accurate localisation of sources in space, in frequency and in time (crankshaft angle). Furthermore, associated to cyclic Wiener filtering, this methodology makes it possible to decompose the overall radiated sound into several noise source contributions whose cyclic sound intensities can then be analysed independently.

Computers and Information in Engineering Conference IDETC/CIE 2009, August 30-September 2, 2009, San Diego,California, USA

[26] S. Delvecchio, G. D'Elia, E. Mucchi, and G. Dalpiaz (2010). *Advanced Signal Processing Tools for the Vibratory Surveillance of Assembly Faults in Diesel Engine Cold Tests*. ASME Journal of Vibration and Acoustics, April 2010, Volume 132, Issue 2

[27] *Blind source separation of internal combustion engine piston slap from other measured vibration signals*, Liu, X., Randall, R.B., 2005, Mechanical Systems and Signal Processing 19 (6) , pp. 1196-1208

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[29] *Diesel engine combustion and mechanical noise separation using an improved spectrofilter*, Pruvost, L., Leclère, Q., Parizet, E., 2009, Mechanical Systems and Signal Processing 23 (7) , pp. 2072-2087

[30] *Separation of combustion noise and piston-slap in diesel engine - Part II: Separation of combustion noise and piston-slap using blind source separation methods*, Servière, C., Lacoume, J.-L., El Badaoui, M., 2005, Mechanical Systems and Signal Processing 19 (6) , pp. 1218-1229

[31] *Separation of combustion noise and piston-slap in diesel engine - Part I: Separation of combustion noise and piston-slap in diesel engine by cyclic Wiener filtering*, Badaoui, M.E., Danière, J., Guillet, F., Servière, C., 2005, Mechanical Systems and Signal Processing 19 (6) , pp. 1209-1217

[32] Antoni, J. (2012), *'A Bayesian approach to sound source reconstruction: Optimal basis, regularization, and focusing'*, Journal of the Acoustical Society of America 131(4), 2873–2890.

[33] Leclere, Q.; Laulagnet, B. & Polac, L. (2005), *Application of an innovative acoustic imaging technique to assess acoustic power maps of a gasoline engine*, in 'proceedings of Forum Acusticum 2005

[34] *The concept of cyclic sound intensity and its application to acoustical imaging*, B. Lafon, J. Antoni, M. Sidahmed, L. Polac, Journal of Sound and Vibration, Volume 330, Issue 9, 25 April 2011, Pages 2107-2121

After describing engine noise, **drivetrain noise** is another relevant source of exterior/interior noise. The configuration of the driveline can result in a variety of NVH concerns across a broad frequency range[35]. Quick changes in the vehicle's load (e.g., pedal tip-in/out) can result in an objectionable vehicle shuffle response, which is connected to the first natural frequency of the driveline and is usually in the 2 Hz – 8 Hz frequency range (depending on the selected gear). On the opposite end of the frequency range, driveline dynamics can influence the dynamic mesh forces of a rear axle, resulting in axle whine, which is typically between 300 Hz – 1 kHz, while transmission whine can extend out to the 3 kHz - 4 kHz range.

A list of the most commonly encountered driveline NVH phenomena and their usual frequency range is shown in Figure 3.

The primary cause of these NVH issues can be traced back to various driveline components or subsystems. Driveline related NVH issues and the corresponding primary sources are shown in Figure 4.

A good approach to characterize driveline noise is the *driveline Sound Quality* is described in Becker et at.[36]. The authors provide a nice analysis of the perception of tonal components generated and/or radiated off the transfer case, transmission, differential and drive shafts. They derive three metrics for transmission tonal noise, all based on fundamental psychoacoustic findings but expressed by simple parameters, such as difference in level between tones and masking. The problem is in finding the maximum allowed level for the tone not to be noticeable against masking. This can be expressed in terms of a smooth 3D surface, like the curved plane shown in Figure 5 which represents the maximum allowed level for the tone as a function of frequency (X axis) and RPM (Z axis). Frequency components sticking out of this plane are clearly audible.

The metrics used to measure the audibility and annoyance of gear noises are surprisingly simple, such as a level difference between the A-weighted SPL of gear-mesh orders and either total noise or bandpassed noise. This level difference is a function of the frequency of the tone and the frequency of the masking, which in turn depends on vehicle operating conditions. One must note that, especially for a classical gear whine issue, the sound quality concern is not so much from the presence of a loud tone, rather from the fact that its' level varies with time/ RPM. Generally in sound quality, change of noise is bad, because it focuses our attention on the noise itself. Often loud noises do not cause complaints simply because they are always present. While a gear whine that, as an example, onsets at exactly 45 mph and goes away at 55 mph, is very noticeable in slight acceleration like passing. For this reason, the maximum level allowed for the tone has to be expressed as a function of RPM, against which measured or predicted gear mesh SPL have to be plotted. The data shown in Figure 6 as an example of clearly audible gear whine at a prop-shaft speed of 700 RPM, because the measured order (in pink) exceeds by 7-8 dB the target curve (in blue). The metrics used for driveline sound quality are: Order slices versus RPM and Tone-over-masking detectability thresholds.

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[35] *Optimizing Vehicle NVH Characteristics for Driveline Integration,* FEV Motorentechnik GmbH

[36] Becker, S., Yu, S., "*Objective Noise Rating of Gear Whine*" SAE 1999-01-1720

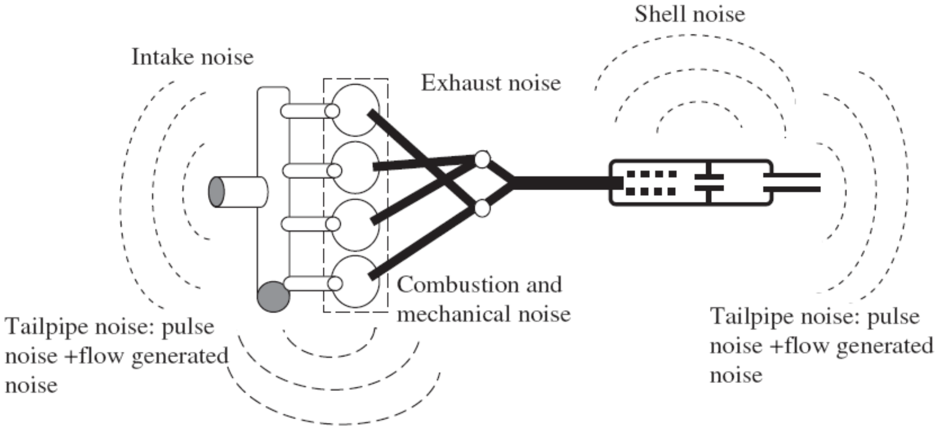
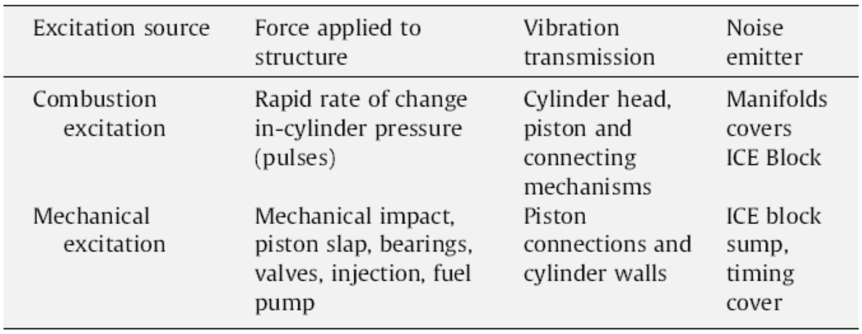


Figure 2 - ICE engine noise sources.



Excitation source	Force applied to structure	Vibration transmission	Noise emitter
Combustion excitation	Rapid rate of change in-cylinder pressure (pulses)	Cylinder head, piston and connecting mechanisms	Manifolds covers ICE Block
Mechanical excitation	Mechanical impact, piston slap, bearings, valves, injection, fuel pump	Piston connections and cylinder walls	ICE block sump, timing cover

Table 1 - Excitation forces and their generation mechanism in diesel engines.

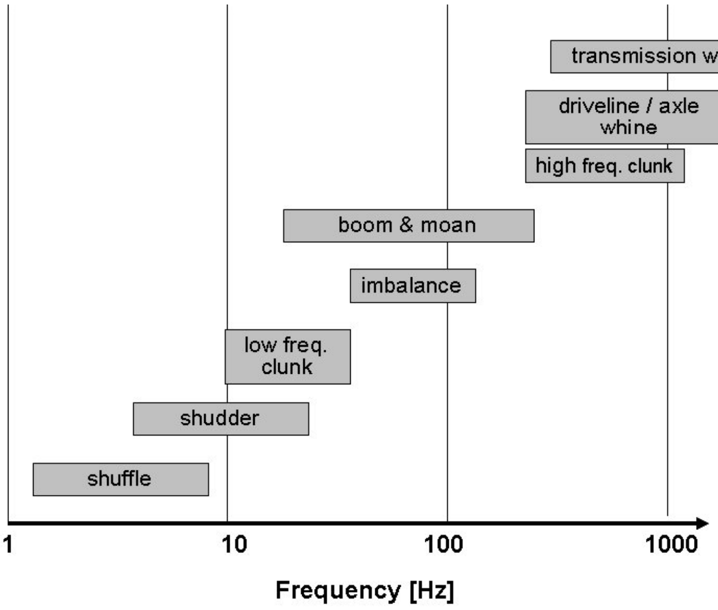


Figure 3 - Typical frequency range of various driveline issues

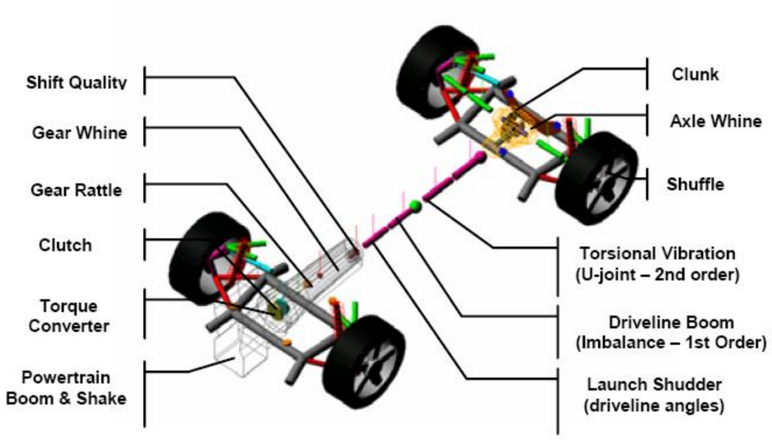


Figure 4 - Typical driveline NVH phenomena

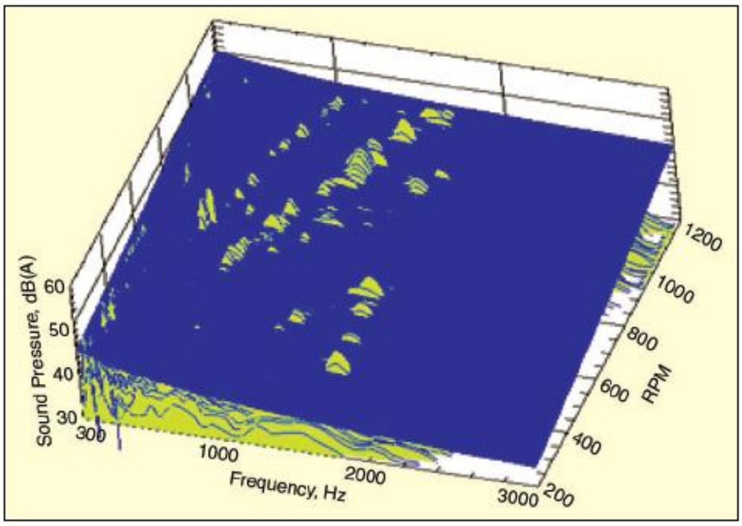


Figure 5 - Tonal noise target surface

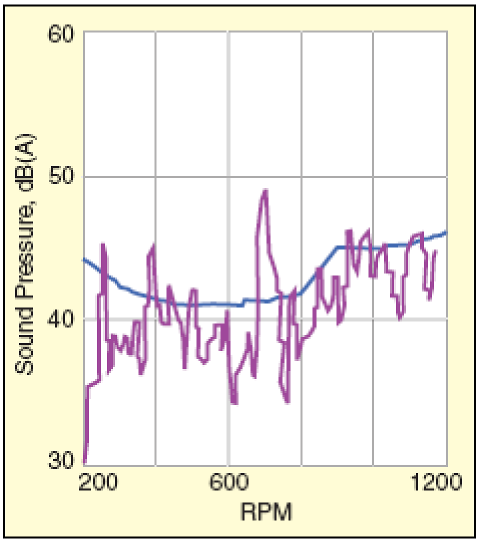


Figure 6 - Measured gear mesh order and target for masking function.

A *systematic methodology* has been developed by Theodossiades et at. for the identification of the main components responsible for the noise radiation in powertrain NVH problems[37]. The main structural modes of the hollow driveshaft tubes that act as loudspeakers have been identified. It has been proven that the elimination of their effects depends on design modifications to the drivetrain system in order to attenuate the impulsive energy waves, which excite them, before the energy reaches the thin tubes. Changes in the shaft geometric characteristics are unlikely to offer much scope, since they cannot shift the structural modes away from the wide-band spectral content of the impulse energy wave. The addition of components that increase the inertia be a solution under certain conditions and may be effective for lower spectral phenomena – such as the transmission gear rattle.

Concerning some specific and localized NVH issues, a *multi body dynamics based approach* is recommended to solve the launch **shudder** phenomenon such that the driveline angles, center bearing bushing dynamic stiffness, phasing angles, and axle mount dynamic properties can be simultaneously optimized.

Boom is another NVH issues that can be defined as an objectionable low frequency noise in the vehicle compartment, which can dominate the overall noise level. Often, a boom noise is caused by driveline resonances, which get excited by the main engine orders. This can be the firing order and its harmonics as well as engine mass forces and moments. In order to understand the root cause of driveline-induced boom, both the driveline dynamics as well as the excitation mechanisms need to be understood. This can be done using *CAE methods*, *testing* or using a *hybrid approach*.

The principal mechanism of **gear whine noise** generation is also studied. This phenomenon is due to the transmission of vibration from the gear shafts and bearings to the differential housing, which is radiated as noise. This has been studied in light trucks by a combination of experimental (i.e. wavelet analysis) and numerical (i.e. elasto-multi-body model) analysis[38]. It is found that the differential oil viscosity affects axle whine by moderately reducing the radiated noise.

The effect of a dual-mass flywheel on impact-induced clonk noise can be also investigated by using experimental techniques[39]. It results that the use of the dual-mass flywheel as a palliative measure can have a beneficial effect on the transient clonk response by transforming it to a milder form of radiated noise. The excitation on the main breathing structural modes of the hollow driveshaft tubes is therefore attenuated.

Electromagnetic noise can be derived from the vehicle alternator[40]. It is found that the alternators sound pressure level is influenced maninly by motor speed. Furthermore, the electromagnetic noise in terms of SPL has a constant ratio of 10% with respect to the alternator total sound pressure level.

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[37] Theodossiades, S., Gnanakumarr, M. and Rahnejat, H. *Root cause identification and physics of impact induced driveline noise in vehicular power train systems*. Proceedings of the Institution of Mechanical Engineers Part D: Journal of Automobile Engineering, 2005, 219, 1303-1319

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[39] Theodossiades, S., Gnanakumarr, M., Rahnejat, H. and Kelly, P. *Effect of a dual mass flywheel on the impact-induced noise in vehicular powertrain systems*. Proceedings of the Institution of Mechanical Engineers Part D: Journal of Automobile Engineering, 2006, 220 (6), 747-761

[40] Saad A., *Vehicle Alternator Electromagnetic Noise Characteristics Determination,* (2009) Proceedings of SAE International paper 2009-01-2188

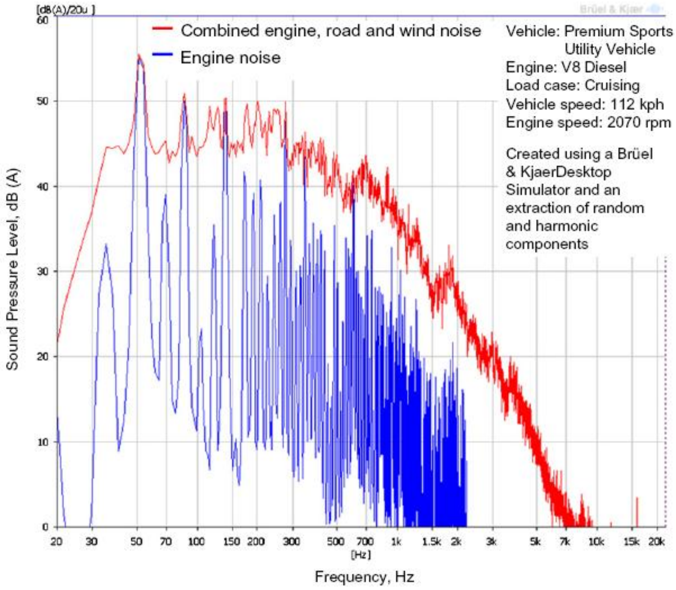

Figure 7 - Contribution of engine noise to the ICE vehicle interior noise

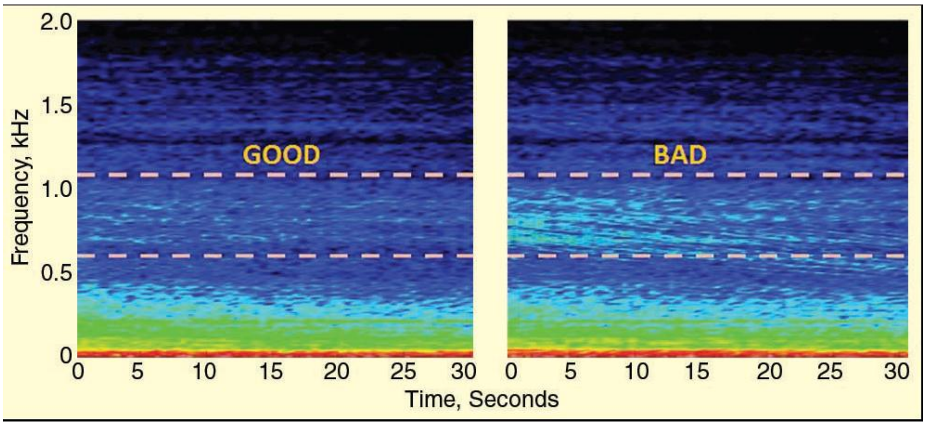

Figure 8 - Example of good and bad road noise quality for "mid-high frequency" concern.

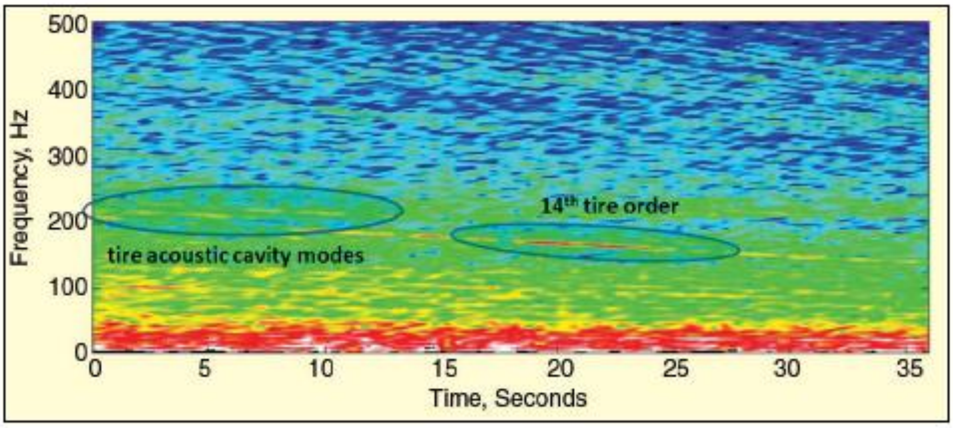

Figure 9 - Example of poor sound quality due to low-frequency tire noise

Other noise ICE vehicle attributes are **road and wind**. An example of engine noise compared to the combined engine, road and wind noise is shown in Figure 7[41]. The data shown in Figure 7 are for a vehicle at a moderate cruising speed of 112 kph. The darker, blue, spectra show derived engine noise, and the lighter, red, spectra show the combined engine, road and wind noise. It can be seen that each noise attribute contributes over a given frequency range. For engine noise, a harmonic signature is present that shapes the lower frequencies in the overall combined spectra even under the vehicle cruising condition. Not only the SPL has to be considered for three sources but the **overall spectral shape** (namely the balance of low and high frequency content that is largely made up of broadband road noise and wind noise, respectively), the **harmonic content** against a **broadband spectral** background and the **directionality of noise sources**. Concerning the latter, as a general principle, if a sound can be perceived as emanating from a specific location within the vehicle cabin, for example, a door seal, then an imbalance in the sound is likely.

Concerning the **road noise**, that is becoming very relevant in the last years, new regulations are recently developped for its contribution to the vehicle exterior noise[42].

Road noise generally starts to be noticeable at vehicle speeds above 30 mph, but its contribution to overall interior noise is maximum between 40 and 60 mph and then decreases at higher speeds, where aerodynamic noise becomes predominant. For this reason, tests for road noise are generally conducted at constant conditions, typically 50 mph and in coast down on different road surfaces. Road noise is generated by the interaction between the tire and the road surface and excites the vehicle through both structural and airborne paths.

An example of good and bad road noise is provided in Figure 8. The FFT color maps represent the analysis of the sound measured at the right ear of a binaural head positioned on the passenger seat of a production sedan driven at 50 mph over a smooth asphalt road (vehicle, road and test conditions are the same between the two plots, the only difference is the tires). As clearly shown, the main difference occurs

between 500 and 1300 Hz, which is the typical “tire-band” range. In this range, both broad-band and narrow-band (tonal) components may be present, due respectively to turbulent type excitation at the tire patch and to tread pitch harmonics. In this frequency range, the path followed by the noise from the tire patch to the interior occupants is airborne; i.e., through holes, leakage, and due to insufficient acoustic transmission loss of vehicle floor, doors, windows.

Since the tire/road noise is generally transmitted only through structural paths (tire-to-wheel-to-tie-rod-to-suspension-tobody) for frequencies up to 200 Hz, the tonal components due to tire acoustic cavity modes are typically structure borne. Alongside the tire acoustic cavity modes, low orders of the tire rotation (related to the number of block elements around the tire) can affect the sound quality. Figure 9 is an example of poor sound quality at vehicle interior due to the presence of both a 14th order of rotation of the tire and two closely spaced tire acoustic cavity modes around 200 Hz.

An extensive study on tyre noise mechanism has been carried out by Eisenblaetter[43] in his Ph.D. Thesis. Data on the separate contributions to traffic noise from rolling and propulsion are analyzed for

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[41] A. Wolfindale, G. Dunne, S.J. Walsh (2012), *Vehicle noise primary attribute balance*. Applied Acoustics 73, 386-394

[42] R. Sohaney et at., New ISO Test Track Specification for Measuring Tire and Vehicle Noise, Sound and Vibration, August 2012

[43] Eisenblaetter, J. *Experimental investigation of air related tyre/road noise mechanisms*, Doctoral Thesis Loughborough University, 2008

Swedish conditions in a preliminary study carried out by Forssén[44] in 2007 in order to investigate the effects of independent reductions of these two kinds of noise sources. From the results it was concluded that there is a must to reduce the rolling noise, in order to reach a total reduction of at least 5 dB, i.e. a sole reduction of propulsion noise is not sufficient. In addition, a sole reduction of rolling noise will also not be sufficient for reaching a total reduction of 5 dB or more, if one looks at the lower driving speeds. In general, for heavy vehicles, a relatively larger part of the total noise is due to propulsion noise, compared with passenger cars. However, for urban driving conditions, which includes lower driving speeds and significantly increased propulsion noise due to acceleration, the propulsion noise of both passenger cars and heavier vehicles needs to be considered.

The article by R. Sohaney[45] explores the possibility of supplementing ISO 10844 measurements with standard tire-pavement noise testing using the on-board sound intensity (OBSI) method. This additional test provides a direct measure of the tire-pavement noise response, which can be compared to the pavement texture being used as an indirect indicator of this response.

An *experimental psychoacoustic analysis* to the **exterior tyre noise** is carried out by Barti[46] who concludes that the overall level (A-weighted) seems not to be correct in order to reflect the nuisance perceived from tire noise. Slick tire shows the lower peak values, but higher energy level and consequently, more noise is emitted by tires. Maximum levels of tire noise does not let us to classify the nuisance of this kind of source. It is necessary a harmonization between measurements in test site and measurements in city. Measurements in test site must reflect the real condition of traffic in city. Slick tire is the noisier of all tires. The main target of some manufacturers is to achieve less peak noise in order to pass the new standard, but this procedure probably is direct wrong because, the human ear is sensitive to energy of sound not to peak values. An experimental campaign was carried out by Lelong[47] who evaluates the contribution to the exterior tyre noise in a vehicle running at constant speed by means of pass-by measurements.

Concerning numerical techniques, *a linear model* is presented by Rustighi for the determination of a random excitation of a tyre's vibration and its subsequent sound radiation[48] for both interior and exterior noise. Numerical methods can also be used for the determination of the point source heights used to model the road vehicle in traffic noise predictions[49]. More generally different sources more than tyre noise can be evaluated by pass-by noise simulation[50]. It is based on the measurement of the individual noise source components, such as engine, intake orifice, exhaust orifice and tires. The transfer functions depend on the position of the vehicle and are measured reciprocally. In the simulation, the individual excitations

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[44] Jens Forssén, *Effect of separately reducing rolling noise and propulsion noise - A preliminary investigation*, Internal Report, Chalmers University of Technology, Göteborg, Sweden, February 2007

[45] R. Sohaney, *New ISO Test Track Specification for, Measuring Tire and Vehicle Noise*, Sound and Vibration, August 2012

[46] Barti, Robert, *Psychoacoustics applied to the tire noise*, Department of Acoustics La Salle, Ramon Llull University Barcelona

[47] Joel Lelong, *Vehicle Noise Emission: evaluation of tyre/road and motor noise contribution*, Proceedings of Internoise 1999, Fort Lauderdade, Florida, USA

[48] E Rustighi, S J Elliott, S Finnveden, K Gulyás, T Mócsai, and M Danti, *Linear stochastic evaluation of tyyre vibration due to tyre/road excitation*, Proceedings of Euronoise 2006, Tampere, Finland.

[49] Hamet et oth., *Acoustic Modelling of Road Vehicles for Traffic Noise Prediction: Determination of the sources Heights*, INRETS paper

[50] Georg Eisele, Norbert Alt and Fabienne Pichot, *vehicle exterior noise and simulation*, Proceedings of ICSV13 Vienna, Austria, July 2006

are synchronized and filtered by the transfer functions. Thus, the total noise can be traced back to the individual transfer paths and the individual transfer paths can be analyzed with regard to excitation, transfer behavior and frequency content. Pass-by-noise has also been studied by Yang[51] who has demonstrated that the low frequency noise of the car is mainly caused by the engine while the high frequency noises are mainly the tire and wind noise. Experiment results have also revealed that the tire and wind noise will grow stronger when the car's speed increases.

Concerning the **wind noise** it is the predominant component of interior vehicle noise at speeds above 100 kph. It is typically tested at steady vehicle speeds between 100 and 160 kph, either on the road or in a wind tunnel. Wind noise refers to the following noise and conditions:

- *Aerodynamic noise* made by the vehicle as it moves at high speed through a steady medium (air). This is related to the aerodynamic (or drag) coefficient of the vehicle, which is a function of the vehicle shape and its cross-sectional area;
- *Aerodynamic noise due to turbulence* through "holes," which is correlated to how tightly sealed the vehicle is (around doors,hood, windshield etc.);
- *Aerodynamic noise* due to exterior varying wind conditions, such as cross-wind on a highway. This is different from the previous two, since this type of wind noise is fluctuating;
- Very low-frequency (10 to 20 Hz) *beating noise occurring* when either a rear window or the sunroof are partially open. This is due to the Helmholtz resonance of the vehicle cabin, which is excited by the air flow along the boundary of the window or sunroof opening. The frequency spectrum of steady wind noise is typically broadband and heavily biased toward the low frequencies (31.5 to 63 Hz);
- *Gusting noise* due to cross-wind, as an example, is impulsive and has content at higher frequencies (above 300 Hz or so). Perception of steady-state wind noise (such as the first two types listed above) is well characterized by *Zwicker loudness*.

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[51] D. Yang, Z.Wang, B. Li, Y. Luo, X. Lian, *Quantitative measurement of pass-by noise radiated by vehicles running at high speeds* Journal of Sound and Vibration 330 (2011) 1352–1364

c. IC vehicle noise path and techniques for path characterization

The classical method of noise source identification[52] is to conduct a disconnection test. If a source is disconnected (e.g. by decoupling the engine mount, putting a total muffler on the air intake system, etc.) and the noise amplitude at the receiving point is reduced significantly, the main root cause is found. However, this only works well if there is a single dominant source (or very few). Even then there is an inherent risk that the disconnection test changed the other contributions, which is often the case if engine mounts are decoupled. With multiple sources of similar contributions this method is not able to give clear results. In such cases, **Transfer Path Analysis (TPA)** works better. The TPA models each connection between the noise source (e.g. vibrating engine) and the receiver (e.g. interior compartment noise or seat vibration) as an excitation (e.g. force input, N) and a transfer function (e.g. receiver sensitivity, Pa/N or $(m/s^2)/N$).

The difference between the calculated response and the measured response can be used as an indicator of the quality of the TPA model. However, even if the calculated response equals the measured response under operation, this is not a proof that the TPA model is exact in every detail. The main problem of the TPA is to get the force input. There are four principal methods:

1. Force method: measure excitation force by introducing a force sensor;

2. Stiffness method: estimate excitation force through, e.g., rubber mounts by multiplying measured relative displacement by measured dynamic stiffnes;

3. Matrix method: estimate excitation force by measuring and inverting the inertance transfer matrix;

4. Operational TPA: estimate excitation force by a least-squares approach of operational data;

Specific TPA applications have been used by Pezerat et at. to recover the main ICE bearing loads [53] and Kim et at.[54] to extract the structure-born noise from the driveline.

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[52] D. Ahlersmeyler, *Advanced experimental techniques in vehicle noise and vibration refinement* in Vehicle noise and vibration refinement Book, edited by Woodhead Publishing Limited, 2010

[53] Leclere, Q.; Pezerat, C.; Laulagnet, B. & Polac, L. (2005), *'Indirect measurement of main bearing loads in an operating diesel engine'*, Journal of Sound and Vibration 286, 341-361

[54] *Prediction of interior noise by excitation force of the powertrain based on hybrid transfer path analysis*, Kim, S.J., Lee, S.K., International Journal of Automotive Technology, Volume 9, Issue 5, October 2008, Pages 577-583

d. IC vehicle Interior/Exterior noise: sound quality and target definition

Any process to address **sound or vibration quality** issues should always start from the voice of the customer to understand what features are objectionable and what are desirable ("1. Assessment" in Figure 11). Once the features are understood then it is needed to find an objective way to quantify them ("2. Measurement in Figure 11). The two steps can actually be performed in parallel as shown in Figure 11.

The purpose of **developing a target**[55] is also to make sure that the OEM is getting the correct material for the vehicle. In doing so, the OEMs conduct extensive benchmarking studies of competitive vehicles under different operating conditions. They identify acoustical parameters of competitive vehicles and opportunities for competitive target levels for the new vehicle. Computer-aided engineering, numerical acoustics, and acoustic measurements participate in developing and optimizing an effective sound package treatment. Computer-aided analysis provides guidance very early in the program. Sound package treatments can be developed using statistical energy analysis (SEA) tools before prototype vehicles are available, reducing development time and cost.

Another purpose of developing a target is to **fulfill the EU regulations**. In December 2011[56] the European Commission published a draft EU Regulation for the sound level of motor vehicles. It proposes more stringent limit values for noise emission than the values currently in force and introduces a new test method as part of the type approval procedure, which is intended to be more representative of the actual conditions in normal urban traffic. Noise limit reduction in 2 steps is proposed in 2013 and 2015 (Phase 1/2/3), each of 2 dB. Other stakeholders have also proposed a further third step of another 2 dB for 2017 (Phase 4/5). Step 1 and 2 would reduce traffic noise levels by around 3 dB, and a third step would reduce it by another 2 dB (around 5 dB in total), assuming a further reduction of tyre noise. Both the 2 step limits and the third step limits are technically achievable. Much of the technology required for further noise reduction is available. This is demonstrated by the fact that part of the vehicles tested between 1 July 2007 and 1 July 2010 already fulfilled the limit values of the 2nd phase of the EC proposal.

For passenger cars 22 % fulfilled the limit value of 68 dB(A) and 3% of 66 dB(A). For smaller vans 11 % fulfilled the limit value of 69 dB(A). For larger vans 6 % fulfilled the limit value of 70 dB(A). For heavy buses 18 % fulfilled the limit value of 75 dB(A) and 8 % of 73 dB(A). For heavy trucks 5 % fulfilled the limit value of 78 dB(A).

Sound/vibration quality parameters[57] can be of the following types:

- Psychophysical descriptors, such as *Loudness, Fluctuation Strength, Roughness*, etc., which are algorithms representing our sensitivity to common, generic attributes of a sound, like *Loudness, Pitch and Timbre*. These are derived from fairly complex psychoacoustic jury studies conducted using elementary synthesized signals, such as sine waves and white noise, on a controlled group of subjects.

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[55] Saha, *Developing Vehicle Sound Packages*, Sound and vibration, October 2011

[56] COM(2011) 856 final, 2011/0409 (COD), *Proposal for a regulation of the European parliament and of the council on the sound level of motor vehicles*, European Commission, Brussels, 9.12.2011

[57] Gabriella Cerrato, *Sound and Vibration Quality Engineering, Part 1 – Introduction and the SVQ Engineering Process, sound and Vibration*, April 2007

- Physical descriptors, such as overall RMS Sound Pressure, octave and third-octave band spectra and all the derived quantities, and statistical parameters describing the temporal behavior of the signal.

Concerning specific sound quality metrics perceptual important characteristics of signals with respect to Diesel Impulsiveness (DI) can be identified, analyzed and quantified with the *NBMA (Narrow Band Modulation Analysis)* method[58] [59]. Starting with the customer relevant perception of interior vehicle sounds this method can be used for the down-cascading of DI via the airborne and structure borne paths to the engine on the total vehicle level.

An automatic noise annoyance detection algorithm (see Figure 10) was developed by Janssenss et at[60]. to extract resonances, masking effects, order non-linearities, booming phenomena and amplitude modulations from an in-vehicle run-up sound and to visualize these noise annoyance features on top of the time-frequency spectrogram of the sound. This algorithm is very useful in closed loop with a Virtual Car Sound (VCS) synthesis tool. Based on the identified noise annoyance features, well-oriented sound modifications can be applied in VCS until a low nuissance target sound is designed. An important benefit of this closed-loop approach is that various sound modifications can be objectively characterized and assessed in a short period of time without the need for extensive jury testing.

Luxury sound quality is another issue that has also been investigated[61]. Through this investigation, it is concluded that the dominant sounds for luxury sound quality are engine sound and mechanical-electric sound. The engine sound includes the acceleration and steady state sound of a passenger car. Mechanical-electric sounds include the operating sound of the sunroof, turn signals and door-locks.

Pass-by noise simulation[62] is a further activity that can support the development activities of car manufactures in this field. It is based on the measurement of the individual noise source components, such as engine, intake orifice, exhaust orifice and tires. The transfer functions depend on the position of the vehicle and are measured reciprocally. In the simulation, the individual excitations are synchronized and filtered by the transfer functions. Thus, the total noise can be traced back to the individual transfer paths and the individual transfer paths can be analyzed with regard to excitation, transfer behavior and frequency content.

Several studies have been carried out in order to understand how to design auditory warning signals that can facilitate safer driving by operators of heavy goods vehicles[63]. One major conclusion is that meaningful warning sounds that are related to the critical event can improve safety. As compared with arbitrarily mapped sounds, meaningful sounds are easier to learn, can improve drivers' situation awareness, and generate less interference and less annoyance.

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[58] Bodden et at. *Diesel Impulsiveness: technical process*, Proceedings of Internoise 2007

[59] Bodden et oth. *Diesel Sound Quality analysis and evaluation*, Proceedings of Internoise 2007

[60] Janssens K., Vecchio A., Van der Auweraer H., *Automatic extraction of noise annoyance features from vehicle run-up sounds*, Proceedings of ISMA 2006

[61] Kyung-Hoon Lee and Dong-Chul Park, Tae-Gyu Kim, Sung Jong-Kim and Sang-Kwon Lee, *Characteristics of the Luxury Sound Quality of a Premium Class Passenger Car*

[62] G. Eisele, N.Alt and F. Pichot, *VEHICLE EXTERIOR NOISE SIMULATION, ICSV13, Austria, July 2006.*

[63] *Designing auditory warning signals to improve the safety of commercial vehicles*, PhD Thesis, Johan Fagerlon, lulea University of Technology

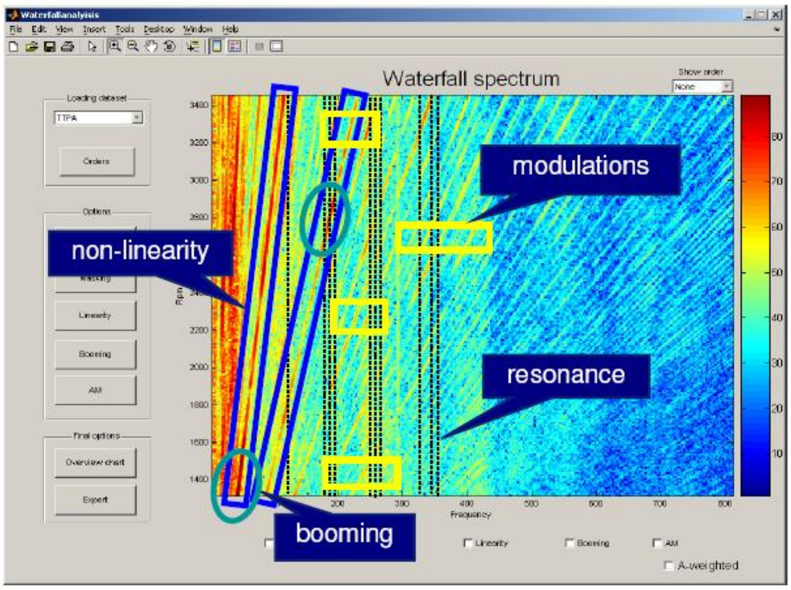

Figure 10 - Algorithm user-interface

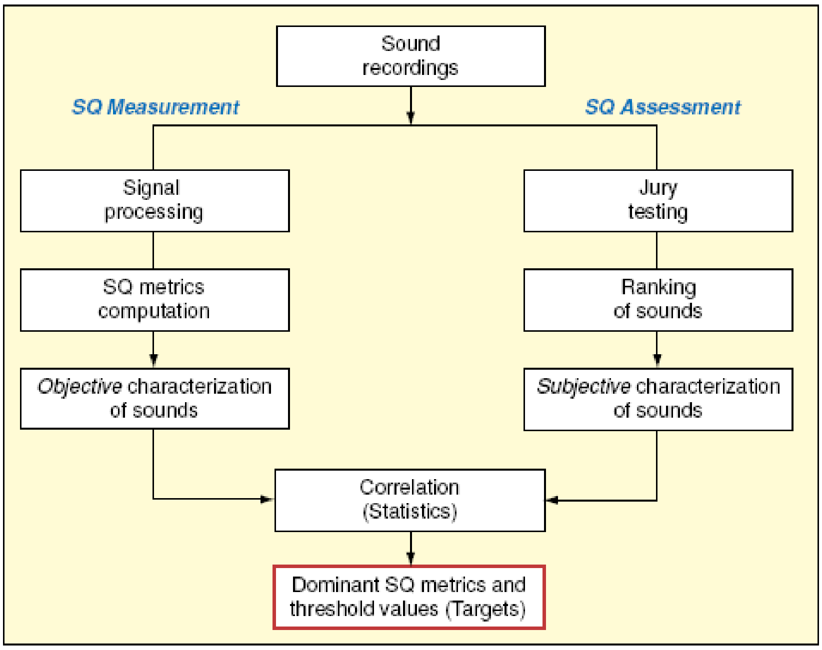

Figure 11 - Sound/vibration quality target development process

In order to design the best quality exterior noise the **active control**[64] of the overall sound quality in a vehicle[65] rather than just sound level can be considered. This may become important in vehicles with variable cylinder management, since the changes in the quality of the sound inside these vehicles as the power source changes 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 minimising it. This has been termed “noise equalisation”[66], “sound

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[64] *A Review of Active Noise and Vibration Control in Road Vehicles* by S.J. Elliott ISVR Technical Memorandum No 981 December 2008

[65] Gonzales A. et at.., *Sound Quality of low frequency and car engine noises after active noise control*, Journal of Sound and Vibration 265 (2003) 663-679

[66] Ji, M.T. and Kuo, S.M. (1993) *Adaptive active noise equalizer*. Proc. ICASSP-93 1 189-192

synthesis[67]", "active design"[68] and "sound profiling"[69], 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"[70]. 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 active control of sound quality in some parts of the automotive industry, who see such electronic sound control as 'cheating' compared to mechanical re-design. As more virtual systems are introduced in vehicles, however, with active braking, stability and steering, and with a younger generation of customer, more used to audio manipulation, these objections are likely to die away.

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[67] McDonald, A.M. et al. (1994) *Sound synthesizer in a vehicle* US Patent 5381902

[68] Scheuren, J., Shirmacher, R. and Hobelsberger, J. (2002) *Active design of automotive engine sound*. Proc. Internoise 2002, paper N629

[69] Rees, L.E. and Elliott, S.J. (2006) *Adaptive algorithms for sound profiling*. IEEE Trans. Speech and Audio Processing

[70] Kobayashi, Y., Inoue, T., Sano, H., Takahashi, A. and Sakamoto, K. (2008) *Active sound control in automobiles*. Proc. Inter-Noise 2008, 112

3. NVH in Electrified Vehicles

a. Introduction

The **electrification of vehicles causes a radical change in the world of NVH**. Decades of experience in designing brand-specific sound, based on noise and vibrations generated by combustion engines, can not be simply transferred to the upcoming electrified vehicles[71]. Although electric vehicles are significantly more quiet, their interior noise is marked by high-frequency noise components which can be subjectively perceived as annoying. Moreover, disturbing noise shares from other components (e.g. oil pump, Heating Ventilation and Air Conditioning (HVAC) system, battery fan, alternator, transmission systems) are no longer masked by combustion engine noise and **give rise to complex sound signatures**. An overview of the NVH issues in EV/HEV and techniques already present in litterature is presented below. From a sound quality standpoint, there are two main design challenges: **interior noise**, which needs to provide an image of quality and "cool" and **exterior noise**, first to ensure safety and next to be used for brand recognition.

b. Electric (EV) and Hybrid Electric Vehicle (HEV) definition

Following the nomenclature as defined in SAE J1715 an **electric vehicle** is a vehicle in which its propulsion is accomplished **entirely by electric motors**, regardless for the means of obtaining that electric energy. An electric vehicle can have one or more energy storage systems. If an electric vehicle has a combustion engine for propulsion power, the combustion engine is not driving the wheels directly through a mechanical transmission.

According SAE J1715 the expression "**hybrid car**" is only used for parallel or combined hybrid systems. In a **hybrid electric vehicle** (HEV) drive power to the wheels can be supplied both by **an electric motor and a combustion engine** working together. This means in certain drive modes, the combustion engine is driving the wheels directly through a mechanical transmission. A hybrid electric vehicle has two or more energy storage systems both of which can provide propulsion power – either together or independently. The engine is typically the larger of the two propulsion sources, being sized to provide most of the power during high power vehicle events. The electric motor is typically the smaller of the two propulsion sources, being sized to maximize the amount of energy that can be captured during braking and for limited low speed EV operation.

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[71] Eisele G., et al., (2010), Electric Vehicle Sound Design - Just Wishful Thinking?, AAC Conference, Aachen, Germany

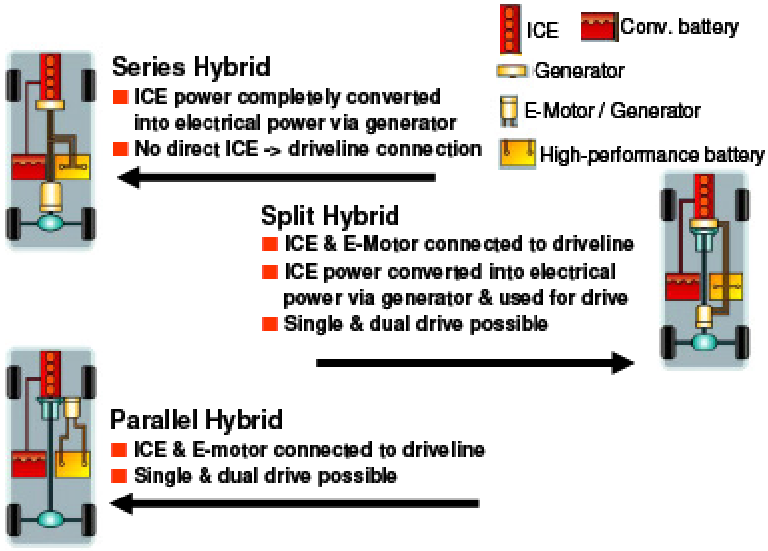

Figure 12 - Hybrid electric vehicle classification

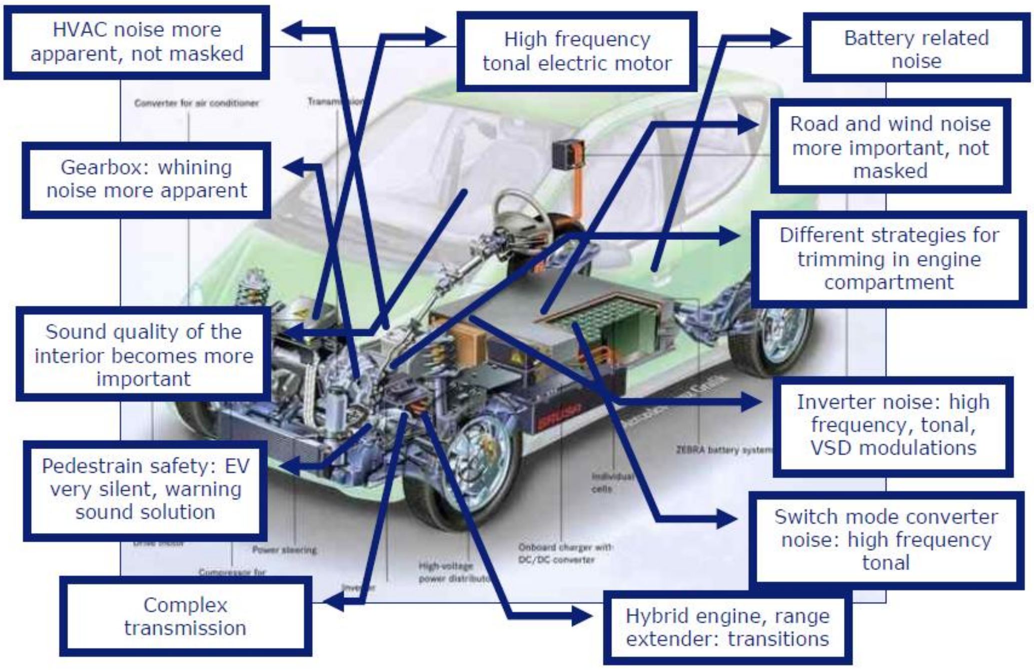

Figure 13 - The increasing complexity of NVH in HEV (summary of SIA papers[72])

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[72] SIA International Congress on NVH of Hybrid and Electric Vehicles, Feb. 4, 2010, Saint-Ouen, France

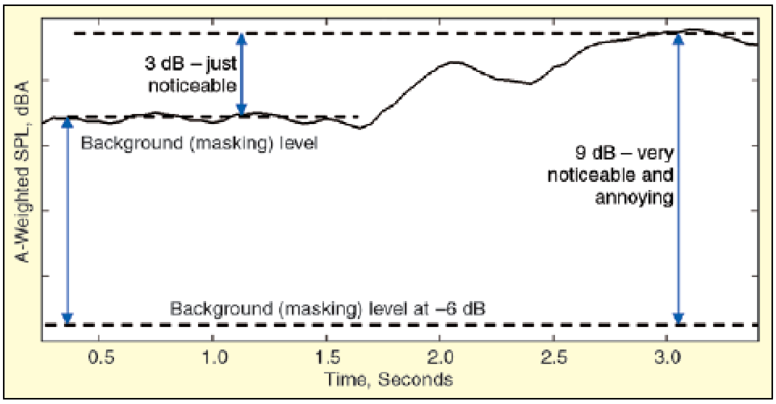

Figure 14 - Change in level due to component start in two different masking scenarios

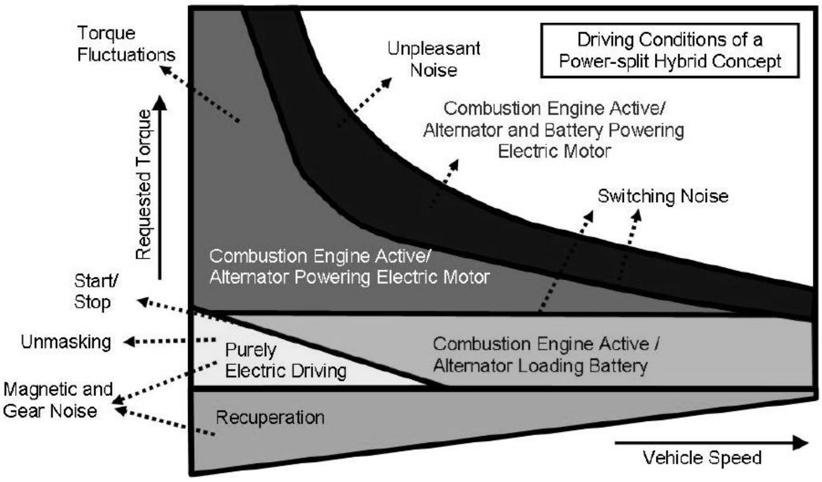

Figure 15 - Noise and Vibration Phenomena of the Toyota Hybrid System in Different Driving Conditions

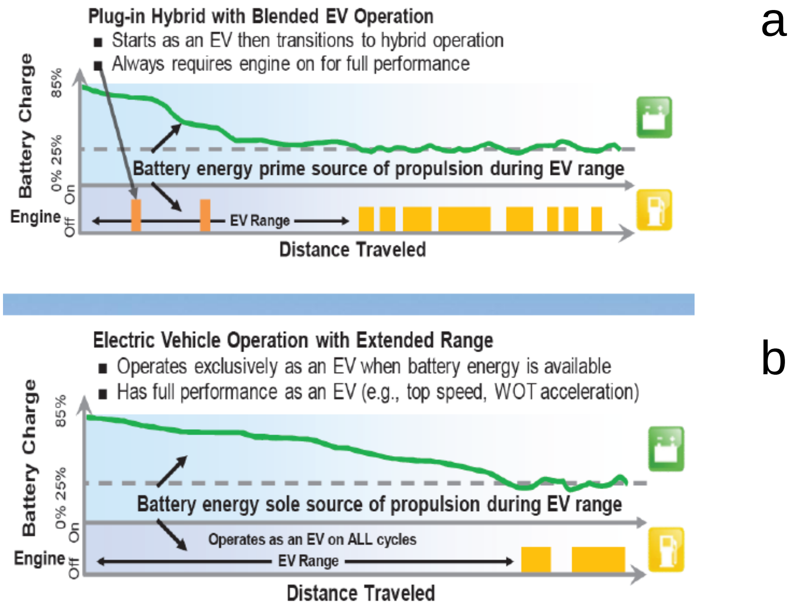

Figure 16 - PHEV and EREV operations

For a given degree of hybridization, **HEV**'s can also be classified based on power flow as **series**, **parallel** and **split hybrid** vehicles[73], as shown in Figure 12. In **series hybrid vehicles**, the ICE power is converted completely into electric power that is used to propel the vehicle so that there is no direct connection between the ICE and the vehicle driveline. In **parallel hybrid vehicles**, the ICE and electric motor are both connected to the vehicle driveline, with many variants possible in both front wheel drive and rear wheel drive combinations. **Split hybrids** typically involve the use of power-split devices that direct the power either in a series or parallel fashion from the ICE and/or electric motor to the vehicle driveline. total cost for energy when compared to a conventional ICE powered vehicle. This reduction in energy cost is possible primarily due to significant differences in energy efficiency of the prime movers. In general, electric motors can operate at energy efficiency above 90% for much of the functional operating range, as compared to only 20-30% energy efficiency for an ICE. Based on currently available battery technology, EV's are expected to be limited to approximately 40 miles of driving on a fully charged battery. In order to provide customers with the flexibility of driving longer distances, developments are ongoing to add an ICE to the EV concept that would extend the driving range of the vehicle. Such vehicles are hence called range-extended electric vehicles (ReEV), electric range-extended vehicles (EREV) or plug-in hybrid vehicles (PHEV) and can be developed in both series and parallel hybrid configurations.

A Plug-in hybrid vehicle (PHEV) (Figure 16 (a))has been defined by SAE J1715 as: "A hybrid vehicle with the ability **to store and use off-board electrical energy in the rechargeable energy** storage system." These systems are in effect an incremental improvement over the Hybrid with the addition of a large battery with greater energy storage capability, a charger, and modified controls for battery energy management and utilization.

Tate, Harpster and Savagian from the General Motors Corporation have defined an **Extended Range Electric Vehicle (EREV)** (Figure 16 (b)) as "A vehicle that functions as a full-performance battery electric vehicle when energy is available from an onboard **Rechargeable Energy Storage System** (RESS) and having an auxiliary energy supply that is only engaged when the RESS energy is not available." General Motors uses the term Extended Range Electric Vehicle to describe its Chevrolet Volt, Holden Volt, Opel Ampera and Vauxhall Ampera, but others in the industry refer to such vehicles as a type of hybrid. This is because for these vehicles in a certain drive mode, the combustion engine is driving the wheels directly through a mechanical transmission.

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[73] Govindswamy K., Wellmann T., *Aspects of NVH Integration in Hybrid Vehicles*, (2009) Proceedings of SAE International

c. Vehicle Interior in EV/HEV vehicles and ICE integration

The increasing complexity of the NVH problem is summarised in Figure 13. The technology used in electrified vehicles is very sparse in literature and it is mainly **experimental**. It differs from the one adopted in conventional vehicles, which also implies differences in terms of noise and vibration behaviour. The engine noise masks certain noise phenomena in a conventional vehicle, therefore when the IC engine is switched off in hybrid vehicles these noise components can become the most annoying ones. In full electric vehicles, the masking effect completely disappears. For these reasons the experimental vibro-acoustic characterisation of the vehicle components/mounting systems and their interaction represents a fundamental starting point for the comprehension of the acoustics inside the cabin.

Concerning **numerical techniques** there is no solution for the numerical simulation of the acoustic radiation of an electric powertrain because adequate multiphysics models are not yet operational[74]. A multibody simulation model of the hybrid drivetrain is developed by Gisele et at[75]. A work carried out by Poxon[76] is involved in creating a HEV model for use within an interactive NVH simulation environment.

The **relevant NVH aspects of hybrid vehicles** fall into three categories: 1 - Dominant noises due to the absence of masking effects (i.e. pump noise of the electric water pump and the vacuum pump, the ventilator and the rolling noise as well as ambient noise) ; 2 - Unexpected acoustic behavior; 3 - Specific acoustic phenomena.

In **the vehicle interior**, when there is no engine, there is no masking, and the noise from all other noise sources (pumps, compressors, fans, etc) becomes suddenly very noticeable. Therefore, the first issue that needs to be addressed is the detectability of all accessories/subsystems, especially when they start and stop. This is illustrated by Figure 14, where the dB(A) function vs. time for a pump on event is displayed (the event occurs at about 1.5 s). With the engine running, the event produces an increase of about 3 dB and, while noticeable, it is not judged to be reason for concern. But if we assume that the background noise was 6 dB lower (and this is a very conservative estimate of the difference between internal combustion engine and electric vehicle **masking**, which may actually be around 15-20 dB) and the pump had the same contribution at the receiver (that is, same source and same path), the delta level at the start of the pump would be around 9 dB(A), which is unmistakably noticeable and annoying.

Figure 17 depicts the interior noise spectrum of a ventilation system at different fan settings. The gray area indicates the interior noise of typical gasoline and diesel engines at idle. It is obvious that the fan noise up to ventilation level 3 is masked by the engine noise. At idle, the fan noise becomes more prominent due to the low engine noise. This has been a steady trend for several years. With hybrid vehicles, a low blower noise becomes even more important due to the fact that the combustion engine is often turned off.

One also has to consider that with an ICE, most of these accessories are driven by the engine (and therefore have expected speed ratio and patterns of harmonics), but in a vehicle powered by an electric motor, the **speed** of pump/fan/compressor may be **unrelated** and may spread over different frequency

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[74] J.-B. Dupont, P. Bouvet (2012) *Multiphysics Modelling to simulate the Noise of an Automotive Electric Motor*, Proc. 7th ISNVH, July 2012, Graz, Austria, SAE International 2012-01-1520

[75] G. Gisele, K. Wolff, M.Wittler, R.Abtahi, S.Pischinger, *NVH of Hybrid Vehicles*

[76] J. Poxon, P. Jennings and M. Allman-Wardt, *Development of a Hybrid Electric Vehicle. A model for interactive customer assessment of sound quality*

ranges. Concerning unrelated phenomena Figure 18 depicts engine speed and vehicle speed of a hybrid vehicle during full load acceleration. Whereas vehicle speed increases continuously, engine speed increases abruptly at the beginning of acceleration and remains nearly constant after approximately 15 s. This speed course generates an interior noise (also known as “the motorboat effect“) that is unusual compared to a conventional powertrain.

Compared to a conventional powertrain, a hybrid powertrain features additional components such as electric engines, electronic control units and a high-voltage battery[77]. This results in different new interactions between these components which are not found in this form in conventional engines.

In the following, NVH phenomena due to hybrid-specific components and their interactions are listed:

- Low-frequency vibrations of the powertrain during start/stop of the combustion engine at load change;
- Modified moments of inertia and eigenfrequencies in the powertrain;
- „Streetcar Noise“: magnetic noise of the engine/generator during electric driving and regenerative braking;
- Aerodynamic noises of the battery cooling system;
- Switching noise of the power control unit.

The **ICE start-up**[78] vibration for HEV and ReEV can be more important since in a conventional ICE powered vehicle, the ICE start up occurs only at the beginning of vehicle operation and the resulting vibration feed-back while for HEV and REEV, the start-up of the ICE is linked to factors such as the state of charge of the battery and driver torque demand., which can result in unexpected vehicle vibration. A significant contributor to the vehicle vibrations during an ICE start-up (or shut-down) event is the excitation of the **engine rigid body modes**, in particular the roll mode of the ICE (motion about the crankshaft axis). Moreover, in conventional drivetrains, the engine start-stop is usually performed with the transmission in neutral and so the torsional vibrations during the start-stop events **are decoupled** from the vehicle driveline. IN case of HEV drivetrains do not necessarily have this decoupling, as a results of which the torsional vibrations from the ICE cranking and combustion phase can excite low-frequency driveline torsional modes such as driveline shuffle. Solutions could be the following:

- Reduction of structure borne excitation, i.e. mount vibration by optimizing mount brackets and location of engine mounts;
- Reduction of structure borne interior noise shares by optimizing the vehicle side mount brackets, body stiffness at mount attachment points, and mount dynamic stiffness.

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[77] Saad A., *Plug-In Hybrid Vehicle Induction Motor Aerodynamic Noise Evaluation,* (2009) Proceedings of SAE International, paper 2009-01-2188

[78] K. Govindswamy, T.Wellmann, G. Eisele *Aspects of NVH Integration in Hybrid Vehicles*

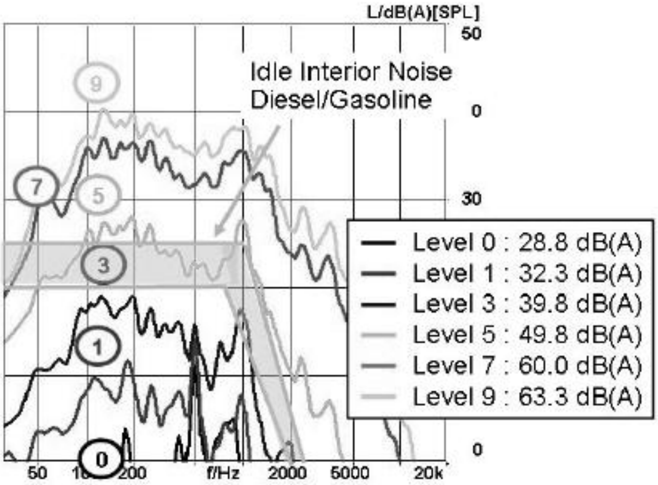

Figure 17 - Interior Noise Spectra of the Ventilation System at Different Fan Settings

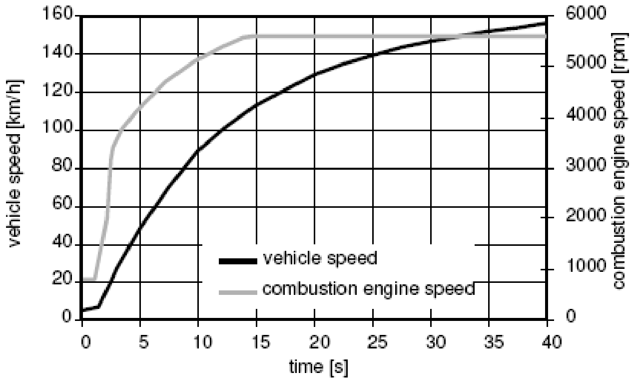

Figure 18 - Course of Combustion Engine Speed during Full Load Acceleration of a Vehicle with Power-Split Hybrid Drive

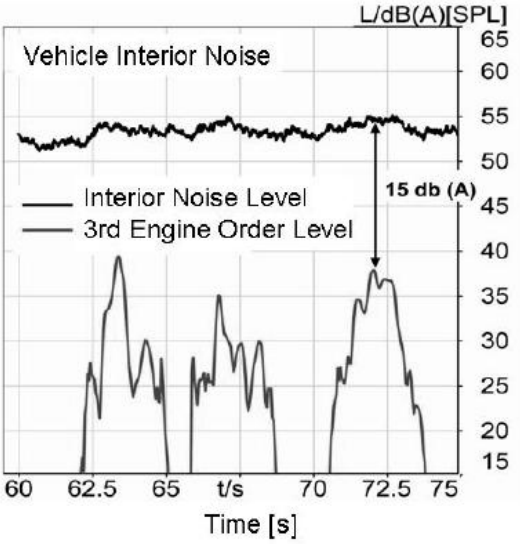

Figure 19 - Interior Noise of Hybrid Vehicle at Constant Speed with Pure Electric Operation and also with Combustion Engine Running

Figure 19 shows an example where the driver hardly notices the change between electric and combustion engine propulsion. It shows a time period from constant driving in which the combustion engine is operated during three short time intervals. Each time the 3rd engine order (6-cylinder engine) appears on the level diagram. However, the level of this order is 15 dB(A) below the total level and thus it is only perceived as a slight background noise. The reason for not providing an acoustic response to the driver in this situation is that the operation of the combustion engine depends on the charge state of the battery and not of the driver's load demand. If during constant driving, suddenly and without any recognizable reason, the combustion engine started up and dominated the vehicle interior noise, it would only serve to confuse the driver.

The electric motor will also generate noise, but typically in a much **higher frequency range** than an internal combustion engine. Its noise can be more easily attenuated by careful design of transmission loss and acoustic absorption of vehicle floor/dash/trunk (depending on the layout of the powertrain). The noise from electric machine such as motors and generators manifests in the form of whine noise, i.e tonal noise (typically in the 40 Hz – 2000 Hz).The tonal nature of the whine noise from the electric machines can be annoying to the customer[79]. Depending on the design of the motor, the **electromagnetic (EM) pulses** and corresponding torque pulses from motor can be very strong. These can be radiated as noise from the motor housing and can also be transmitted structurally through the motor mounts.

Electrical components could be studied separately by using signal processing techniques[80] [81].

Two interior noise components that are unchanged are **road** and **wind** noise. Not only are their relative contribution to overall interior noise larger in electric vehicles but also they may be the only elements providing acoustic feedback to the driver with regard to vehicle speed and acceleration. Since they cannot be suppressed completely, the overall sound quality balance of the electric vehicle has to be designed around their temporal pattern and frequency characteristics.

An *interesting experimental campaign* on hybrid vehicle was carried out by Genuit[82] shows the measurement of a run-up from 0 to 50 km/h, which was measured on a four-wheel chassis dynamometer. It can be clearly seen in the diagram that the electric drive operates at first and during acceleration the combustion engine begins to operate. In the Figure 20 it is observable that an annoying noise around 7 kHz occurs which is caused by the power inverter. Moreover, at 7.5 s the combustion engine starter noise can be perceived. At 11 s an increase of the engine roughness in the range of 300 to 500 Hz is observed due to the load taken over by the combustion engine. Before, the whine noise (500 - 2000 Hz) of the electric motor can clearly be heard. Figure 20 displays that the whine orders, caused by magnetic forces of the electric motor, are transferred not only as structure borne noise, but are also radiated directly from the motor and inverter. This fact directly drives requirements for sound quality optimization. Further noise patterns are the inverter switching noise (airborne) and low frequency booming of the electric motor (structure borne).

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[79] Greg Goetchius, *Leading the Charge The Future of Electric Vehicle Noise Control*

[80] L.R. Padovese, *Hybrid time–frequency methods for non-stationary mechanical signal analysis*, Mechanical Systems and Signal Processing 18 (2004) 1047–1064

[81] C. Cristallia et at. *Mechanical fault detection of electric motors by laser vibrometer and accelerometer measurements* Mechanical Systems and Signal Processing 20 (2006) 1350–1361

[82] K.Genuit, *The Change of Vehicle Drive Concepts and their Vibro - Acoustical Implications*, Symposium on International Automotive Technology 2011

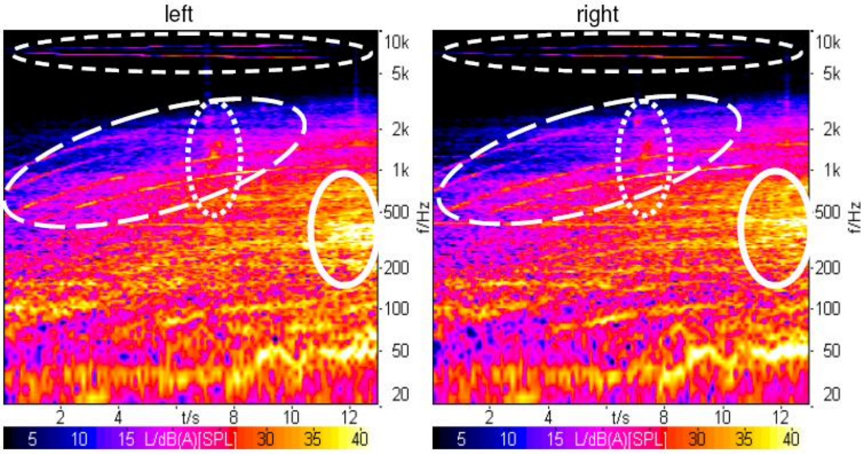

Figure 20 - Binaural interior noise spectrogram of run-up 0-50 km/h showing whine noise, inverter noise, engine start at 7.5 s and roughness increase at 11 s; FFT vs. time

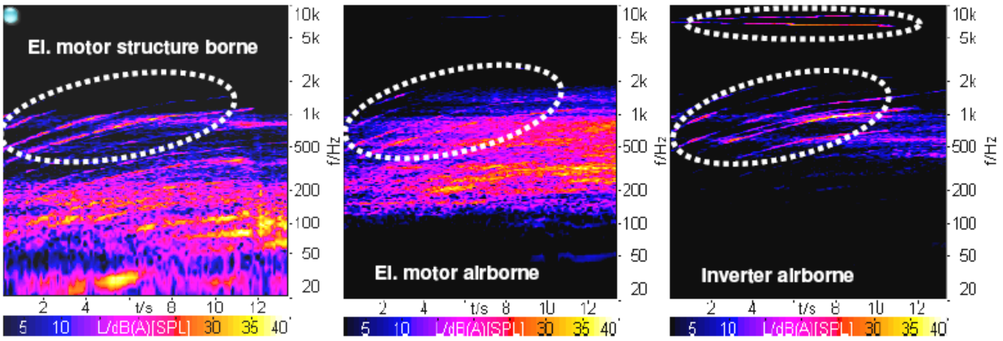

Figure 21 - Interior noise contribution of electric drive components

d. Vehicle exterior in EV/HEV vehicles and sound generation

For green vehicles, electrification involves a major challenge on the **audibility** of these vehicles which conflicts with passenger expectations and OEM branding and impacts road safety issues[83,84].Their quietness poses a major hazard for vulnerable road users, including the elderly who probably have developed pres by cusis, as well as the blind and the visually impaired[85,86,87], made worse in places of high ambient traffic noise levels.

Electric/hybrid vehicles at low speed (in a parking lot) tend to run on the electric motor only, so they are extremely quiet. Pedestrians use auditory as 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. This is of utmost importance for the blind community, which obviously relies exclusively on auditory cues for detecting approaching vehicular traffic. With this issue in mind, the automotive industry in North America has formed a Society of Automotive Engineers subcommittee to investigate this growing concern and develop recommendations. The most commonly devised solution is for the electric vehicle to generate exterior noise by means of loudspeakers mounted on its front section.

Most references[88] to the risks posed by quiet hybrid vehicles are contained in magazine, newspaper and online articles or position statements from various interest groups. None appear to be based on any form of scientific testing, though a number claim to reflect real life experiences of vision impaired, and in some cases, sighted persons.

In addition to these studies, the US National Highway Traffic Safety Administration in September 2009 released its Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles[89]. This study was exploratory in nature and was intended to guide researchers when designing pedestrian and bicyclist crash prevention research. It examines the incidence rates of pedestrian and bicyclist crashes that involve hybrid electric vehicles and compares the results to conventional vehicles under similar circumstances. An analysis was conducted on a total of 8,387 hybrid vehicles and 559,703 conventional vehicles, of which 77 and 3,578 respectively were involved in crashes with pedestrians. A total of 48 and 1,862 respectively were involved in crashes with bicycles. The study found that **pedestrian and bicyclist crashes involving both hybrid and conventional vehicles commonly occurred on highways, in zones with low speed limits, during daytime and in clear weather, with higher incidence rates for hybrids when**

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[83] Knopp G. "*Strategies and methods for multi-material structure and concept developments*" International Conference "Innovative Development for Lightweight Vehicle Structures" May 2009, Ed. Volkswagen

[84] George, TJ: *Development of a Novel Vibration-based Fatigue Testing Technology*. Int. J. Fatigue 26 (2004) pp. 477-486

[85] European Blind Union - http://www.euroblind.org/fichiersGB/nl69.htm

[86] The National Federation of the Blind – Committee on Automobile and Pedestrian Safety/Quiet Cars http://quietcars.nfb.org/

[87] ANEC – The European consumer voice in standardisation, Position Paper: *Silent but dangerous: when absence of noise of cars is a factor of risk for pedestrians*, 2010. http://www.anec.org/attachments/ANEC-DFA-2010-G-043final.pdf

[88] R. Manning, *Audible detection of approaching hybrid and petrol powered vehicles in the urban environment*, RACQ Report, August 2010

[89] US National Highway Traffic *Safety Administration Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles* September 2009

compared to conventional vehicles. A variety of crash factors were examined to determine the relative incidence of rates of hybrid vehicles versus conventional vehicles in a range of crash scenarios. For one group of scenarios, those in which a vehicle was slowing, stopping, backing up or entering or leaving a parking space, a statistically significant effect was found due to engine type. Hybrid vehicles were two times more likely to be involved in a pedestrian crash in those situations than was a conventional vehicle. Vehicle maneuvers such as slowing, stopping, backing up, or entering or leaving a parking space, were grouped in one category because these maneuvers potentially occurred at very low speeds where the difference between the sound levels produced by the hybrid versus the conventional vehicle is the greatest. The **incidence rate of pedestrian crashes in scenarios when a vehicle makes a turn was found to be significantly higher for hybrid vehicles when compared to conventional vehicles.** The study found no statistical difference in incidence rates of pedestrian crashes involving hybrids when compared to conventional vehicles when both types of vehicles were going straight. Crashes involving bicycles and hybrid vehicles that were slowing, stopping, backing up, or entering or leaving a parking space were found to be significantly higher when compared to conventional vehicles. The roadway was the most common location of bicyclist crashes involving both hybrid and conventional vehicles, though there was no statistically significant difference in the type of car involved in the crash. However, bicyclist crashes involving hybrids at intersections were significantly higher when compared to conventional.

4. Concluding remarks

This report represents a state-of-the-art synthesis of current knowledge in NVH issues concerning ICE and Electrified Vehicles.

The Electrified Vehicles presents a number of relevant differences in NVH behaviour with respect of ICE vehicles. They main differences concern:

- multiple rotating components with order interactions;
- different sources;
- different testing conditions have to be tested (cruise, braking, acceleration, deceleration, full load, idle):
- high frequency noise and tonal components;
- low frequency resonances due to new driveline configuration (with presence of electric motor and generator;
- less variations with load while ICE vehicles are very load dependent.

Concerning **experimental techniques**, only a few sparse activities have been carried out for Electrified Vehicles (i.e. TPA). No **numerical models** have been developed.

On the other hand for ICE vehicles **advanced experimental techniques** such as source separation, force reconstruction, acoustic imaging and active control have been developed.