

COMPARISON OF EXPERIMENTAL METHODS TO MEASURE THE AEROACOUSTIC NOISE OF AUTOMOTIVE ROOF CROSSBARS

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Abstract. *Aeroacoustic noise reduction is one of the growing concerns in the automotive industry. With the advances in the suppression of powertrain and tire airborne noise, wind noise has become the dominant noise source propagating to the passenger cabin in cruising speeds. Automakers have invested a reasonable amount of resources to investigate noise mechanisms and mitigate them, in order to meet aggressive comfort requirements. The most severe aeroacoustic noise phenomena in ground vehicles are the ones with a tonal nature. The presence of discrete tones during vehicle operation is unacceptable, and one of the most critical components in terms of noise performance are the roof-mounted luggage carriers, which typically have a leading crossbar with direct exposure to the airflow. The tonal noise from roof bars, when not addressed, can be very annoying to the customer. Nowadays, most of the applied solutions to this aeolian tone are empirical, sustained by the fact that commercial crossbar profiles are not as blunt as a cylinder, neither as thin as a wing section. The objective of this project is to investigate the noise mechanisms involved in typical crossbar shapes experimentally. The first part of the study was made by correlating measurements made on-track at the General Motors Brazil Proving Ground and in the Aeroacoustic wind tunnel of General Motors North America. Interior and exterior sound pressure level measurements taken on-track and at the wind tunnel were compared. The results show that exterior microphones used on-track are capable to properly capture both tonal and broadband noise contribution of the crossbars despite of the background noise, thus being the method adopted to continue this project.*

Keywords: *Aeroacoustics, Automotive, Blunt body, Wind Noise*

1. INTRODUCTION

1.1 Aeroacoustics of vehicle crossbars

Roof-mounted luggage carrier crossbars have become a very popular feature of ground vehicles as the global market demand for small, mid and full-size Sport Utility Vehicles (SUV) and Crossovers has increased drastically over the years. Automakers are offering roof racks as a standard content rather than optional in several models. In parallel, accessory roof carriers are increasingly popular as they are used for holding sports gear and many other types of load.

From the wide range of vehicle's exterior parts that generate airflow noise, e.g. outside mirrors, roof antennas and wipers, roof racks are the most critical in terms of aeroacoustic performance. The noise contribution of a roof rack is both tonal and broadband in nature. The characteristic aeolian tone, without countermeasures, is capable to reduce cabin articulation index drastically in steady cruising speeds, causing annoyance to the vehicle occupants. The aeolian tone is described as a low frequency "howl" and invariably leads to customer complaints if not mitigated. The broadband noise is less intense and less severe to customer perception, but also requires attention during development.

Figure 1.A shows the noise contribution of typical crossbar with no solution applied, measured on-track at 120km/h. The microphone is installed inside the vehicle cabin at driver's position. The experiment will be further described in the section Experimental method of this paper. Both tonal and broadband increments are seen within the 100 to 1kHz range. Two main tones are concentrated at the 192Hz and 608Hz frequency bands, and the broadband noise increment extends up to approximately 1kHz. The increment from the aeolian tones is about 8 dB inside the vehicle cabin under normal operational condition, what shows the severity of the phenomenon.

The aeolian tone is usually attributed to the crossbar shape, as a result of the direct exposure of the crossbar to the exterior airflow. Isolated component tests over many types of roof racks have proven the aeolian tone is generated by the interaction of the crossbar with the air stream, whilst the longitudinal side rails and stanchion mechanisms contribute to the broadband noise generated by the roof rack system (Figure 1.B). Side rails and stanchions can eventually generate discrete high frequency tones known as "whistles", but the main contributor to the roof rack system tonal noise is beyond question the crossbar. Kingan and Pearse (2006) describe other noise sources involved in roof rack systems such as edge tones and wake-roof interaction, but also defines the crossbar self-noise as the primary noise source in the system.

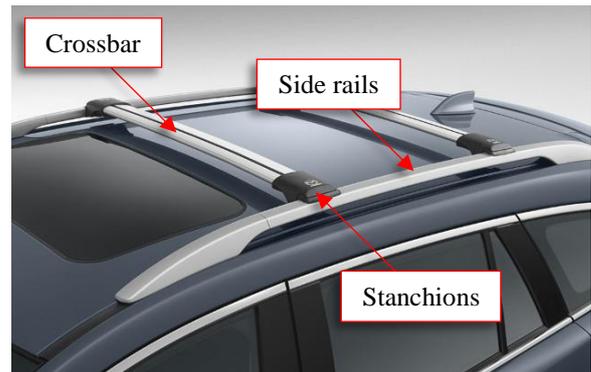
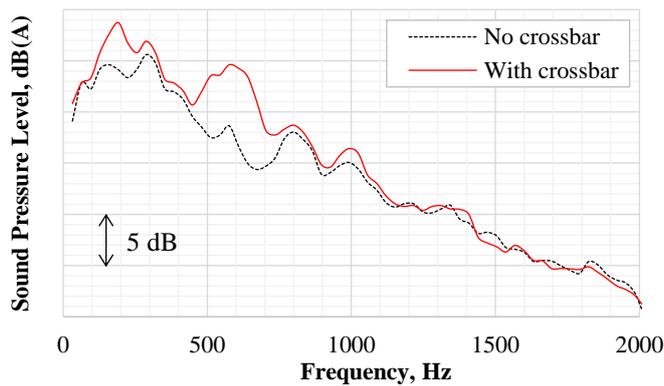


Figure 1.A: Noise contribution of a typical crossbar with no countermeasures, measured on-track with interior microphone at driver position and vehicle speed of 120km/h; 1.B: Typical crossbar, stanchions and side rail system.

Nowadays, most of the applied solutions to the aeolian tones are empirical. The design of a roof bar involves a number of criteria such as appearance, packaging, structural stiffness, aerodynamic drag and manufacturing process. The crossbar sections are typically not chosen for their aeroacoustic performance and the solution to the aeolian tone is typically applied experimentally after the basic cross-sectional shape dimensions are defined. In some cases, the solution is the addition of features or extra parts, which end up increasing part complexity, tooling and/or piece cost, as well as potentially jeopardizing style, aerodynamics and broadband noise performance.

One of the rationale behind that is the fact that correlated Computational Aeroacoustics methods applied to roof rack design are not readily available to most of automakers and suppliers. Accurate prediction is difficult and time-consuming due to the complicated flow physics that occurs in the near wake. Typically, noise predictions require computationally demanding three-dimensional flow simulations that are usually not practical for engineering use (Doolan, 2009). Therefore, most of manufactures are not capable to predict early in the development process whether a conceptual bar shape will generate an audible discrete tone, thus developing an optimum solution during early geometric release phases. In other words, despite the fact that the aeolian tone is a severe phenomenon that affects the component design, its noise generation mechanisms are not fully understood, and the solutions are typically developed empirically during full-scale clay model and integration vehicle wind tunnel testing, when most of the design boundaries are freeze.

1.2 Noise generation mechanism

Several geometrical factors affect the aeroacoustic self-noise of a roof rack crossbar. The critical controlled factor is the crossbar shape: thickness, chord, angle of attack and profile, including symmetry (Figure 2.A). Other factors such as longitudinal position and height (related to the boundary layer formation on the vehicle roof), surface roughness and cross-car curvature are secondary factors highly constrained and more difficult to manipulate. This project assumes the roof crossbar is immersed in free-stream laminar airflow with low turbulence intensity and out of the roof boundary layer due to distance-to-roof package requirements. It is also assumed that the surface roughness is as smooth as it typically is in commercial roof bar materials (e.g. Aluminum extrusions), giving focus on the bar shape parameters.

One of the difficulties to understand the noise mechanisms of a roof crossbar shape is the fact that commercial crossbar profiles are not as blunt as a cylinder, neither as thin as a wing section. The physics involved in both types of bodies is well understood, but the automotive roof bar shapes are between those conditions. Figure 2.B shows four commercial extruded roof bar sections, two of them with package for rubber inserts. None of those is as short as a cylinder, neither as thin as a wing section. For these typical shapes, characteristic Reynolds is within the 80,000 to 300,000 range, and the operational Mach is very low, between 0.05 and 0.2.

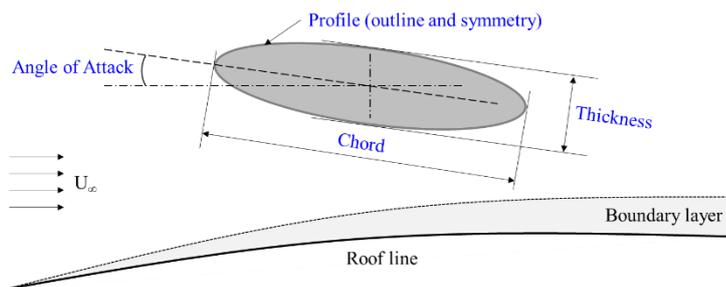


Figure 2.A: Shape factors affecting crossbar self-noise; 2.B: Commercial Aluminum extrusion crossbar sections.

In a circular cylinder, the aeolian tone is caused by the periodic shedding of vortices on the lee side of the cylinder immersed in the airflow. The boundary layers formed at the leading edge of the cylinder separate at the trailing edge near the top and bottom of the cylinder and form shear layers with periodic oscillation that grow behind the cylinder and form the von Karman vortex street (Figure 3.A). The oscillating pressure caused by the vortices meets the rear surface of the cylinder and create a source of sound that propagates as a dipole, i.e. the aeolian tone (Doolan, 2009). For Reynolds numbers above 80,000, typical of roof bar applications, the turbulent wake has the fundamental mechanics of the von Karman vortex street, added to three dimensional velocity fluctuations of many different scales (wavelengths). These three-dimensional pressure fluctuations also meet the rear cylinder wall and generate a broadband effect of the aeolian tone and its harmonics (Doolan, 2009). The fundamental frequency of the tone (f_0) emitted by a circular cylinder is given by the fundamental Strouhal number ($St_0 \approx 0.2$), where $f_0 = St_0 U_0 / D$ (Strouhal, 1878). D is the cylinder diameter and U_0 the free stream velocity. The frequency of the tone increases with the velocity of the airflow and decreases with the increase of cylinder diameter.

In an airfoil, aeroacoustic phenomenon is more complex. There are five known self-noise noise generation mechanisms involved in subsonic flow conditions: laminar boundary layer vortex shedding noise (low Reynolds flows); turbulent boundary layer trailing edge noise (high Reynolds); trailing edge bluntness vortex shedding noise (circular cylinder noise mechanism); boundary layer separation and stall noise; and tip vortex formation noise (Brooks and Pope, 1989). In automotive roof bar applications, tip vortex noise and deep stall noise do not occur. The other mechanisms, also referred as trailing edge noise or boundary-layer instability noise, occur and generate both broadband and tonal nature noise.

At low Reynolds number, the flow over airfoils has different characteristics from that found at high Reynolds number. At $Re = 50,000$ and 0° angle of attack (Sandberg et al., 2008), laminar boundary layers form initially on the airfoil leading edge surfaces, but differently from the circular cylinder, unsteady disturbances appear (Tollmein Schlichting or T-S waves). These are the first stages of the boundary layer transition to a turbulent state, and depending on the flow regime, they can separate and create oscillating shear layers that interact with the trailing edge, developing a complex wake behavior and noise generation mechanism which further involves diffraction and scattering of the acoustic waves. Different from the circular cylinder dipole radiation, the directivity of the acoustic waves presents a cardioid pattern whose mechanism is remarkably described by Arcondoulis et al., 2010: the noise sources within the boundary layer are represented by quadrupoles that can be considered as a pair of dipoles with orthogonal axes. When a dipole wave encounters the airfoil edge, a diffracted wave is produced and travels back towards the quadrupole with opposite phase. This diffracted wave combines with outgoing waves from the other side of the dipole to create an efficient source of sound. In this way, one side of the quadrupole is made an efficient radiator of sound and results in the cardioid directivity pattern associated with trailing edge noise (Figure 3.B).

The generated noise is classified either as tonal and broadband, and contains a superposition of primary ($f_{n,max}$) and secondary (f_n) narrowband tones on a broadband hump (Arbey and Bataille, 1983). Broadband noise is due to a large number of incoherent eddies with a variety of scales and strengths, and the tones are due to reasonably coherent and strong eddies in the trailing edge near wake. The discrete tones measured experimentally for the NACA0012 profile can be described in a ladder-structure plot in function of the airstream velocity, and the primary tone is fitted by the curve $f_{n,max} = 0.011U_0^{1.5}/\sqrt{Cv}$, where C is the airfoil chord length and v is the kinematic fluid viscosity (Arbey and Bataille, 1983). The main frequency has a Strouhal number and airfoil thickness dependence. There is still no formal method for determining which angle of attack and Reynolds number causes the greatest tonal sound pressure level for an airfoil under low Reynolds number flow conditions, and there is no general consensus amongst the acoustic community of the precise cause of trailing edge noise primary and secondary tones (Arcondoulis et al., 2010). The strongest hypothesis is that at certain frequencies the sound is amplified via an acoustic feedback mechanism near the trailing edge, but the physics of the feedback mechanism is still unclear. A summary of the various proposed causes for the tonal noise and the feedback mechanism is given by Arcondoulis et al. (2010). It is also known that depending on the angle of attack, airfoil geometry and the Reynolds number, discrete tones do not occur (Lowson et al., 1994). Ramirez and Wolf (2015) also demonstrated a direct relation of the trailing edge bluntness to the occurrence and characteristics of the narrowband tones.

The self-noise emitted by ground vehicle crossbars approximate to both circular cylinder and airfoil trailing edge noise behavior in low Reynolds flow regimes. It can be assumed that, the higher is the bar profile thickness ratio, the more it will approximate to the circular cylinder tonal noise characteristic. What is seen in thinner bar profiles is that more than one narrowband tone can occur, as well as do not occur for some angles of attack, what goes in the direction of airfoil trailing edge noise behavior. Given this scenario, the objective of this project is to investigate the relation of the crossbar geometry to the discrete tones, with the aim to identify trends determining in which conditions typical crossbar shapes will or will not generate the objectionable tones.

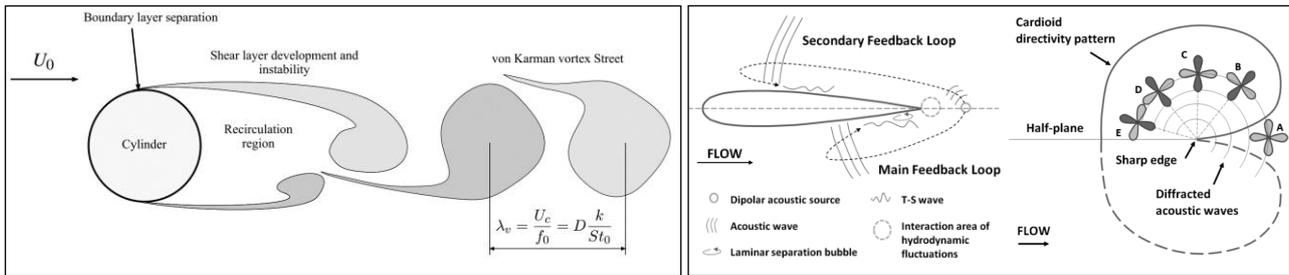


Figure 3.A: Noise generation mechanism in a circular cylinder (adapted from Doolan, 2009); 3.B: Noise mechanisms in wing profiles (adapted from Arcondoulis et al., 2010).

2. EXPERIMENTAL METHOD

The method chosen to evaluate the crossbar self-noise is based on actual acoustical measurements. The most practical way to run this project is on-track testing at the General Motors Brazil Proving Ground. Prototype parts, test vehicle and data acquisition equipment is readily available. Acoustic data acquisition was performed on a 2.5km long smooth asphalt straightaway track with uncontrolled ambient condition (air temperature, humidity, ambient wind speed and direction). Given the uncontrolled ambient condition, the first part of this project was made by correlating measurements made on-track to measurements made in a totally controlled and acoustic isolated ambient: the Aeroacoustic wind tunnel of General Motors North America. The same vehicle and parts were tested in both sites and results were compared. The objective of the first part of the project is to identify whether on-track tests are reliable enough to analyze noise spectra from different crossbar geometries in despite of the uncontrolled ambient.

2.1 On-track testing

On-track tests were performed at the smooth asphalt straightaway track of the General Motors Cruz Alta Proving Ground, located in the city of Indaiatuba, SP, Brazil. The track has two straight flat sections of 2.5km each, interconnected by 180° tilted rounds (Figure 4.A). Data acquisition was taken uniquely at the track side with less exposure to crosswind. Ambient conditions were monitored during the test to avoid ambient wind speeds above 3m/s and high temperature gradients. Each series of acquisition did not last longer than 2 hours to avoid drastic ambient condition changes. In order to minimize powertrain airborne noise during test, the lowest gear ratio available and cruise control were used to maintain low and stable engine rotational speed.

2.2 Wind tunnel testing

Wind tunnel tests were executed at the General Motors Aerodynamics Laboratory (GMAL), located at the General Motors Warren Technical Center in Michigan, United States. The facility is used for aerodynamic shape development, cooling airflow optimization and aeroacoustics. The closed-jet test section (Figure 5.A) is 5.5m high, 10.4m wide and 21.7m long, and is the largest wind tunnel in the world dedicated to automotive testing. The stationary floor test section is semi-anechoic and the 301m long air path is acoustically treated. The interior surface of the air path has acoustic absorption panels consisting of fiberglass batting behind perforated sheet metal panels, and turning vanes are acoustically treated to absorb background noise.

2.3 Data acquisition and signal processing

For interior and exterior noise measurements, Brüel & Kjaer 1/2" microphones type 4943 and preamplifiers Brüel & Kjaer type 2669 were used. The exterior microphone was located at vehicle centerline 300mm above the roof crossbar and perpendicular to the radiated noise. Microphone stands were developed in-house for this application. The transducers were calibrated using the Brüel & Kjaer microphone calibrator type 4231. In all exterior measurements, Brüel & Kjaer nose cones type UA-0386 were used to reduce the aerodynamically microphone self-induced noise. The cone has a streamlined shape with a highly polished surface in order to give the least possible resistance to air flow. A fine wire mesh around the nose cone permits sound pressure transmission to the microphone diaphragm while a truncated cone behind the mesh reduces the air volume in front of the diaphragm. For interior and exterior sound pressure level measurements, channel A-weighting was applied, and the frequency resolution was set to a narrowband bandwidth of 32Hz. The frequency range covered the range from 160Hz to 16,384Hz with linear averaging and 50% overlap. The gain of each channel was set to maximize signal but avoid overloads. The frequency domain spectral plots were calculated using a Fast Fourier Transform (FFT) analyzer.



Figure 4A: Test track; 4.B: Interior microphone; 4.C: Exterior single microphone and strut.



Figure 5A: Wind tunnel test section; 5.B: Interior microphone; 5.C: Exterior single microphone and strut.

3. RESULTS

In order to assess the on-track testing method, the leftmost crossbar shown in Figure 2 was adopted. It has a known acoustic performance, i.e. an audible aeolian tone noticed inside the vehicle cabin at speeds above 70km/h, and a known solution that mitigates the tone. The crossbar profile is symmetrical and has a streamlined outline with moderate bluntness.

Figure 6 compares the spectral content of on-track and wind tunnel measurements taken inside the vehicle with and without the crossbar, at the speed of 120km/h, where the aeroacoustic airborne noise is the dominant source. The spectral behavior without the crossbar is similar but has an offset due to the presence of tire and engine airborne noise on-track, as well as due to an intrinsic test procedure difference. At the wind tunnel, data is taken with the driver quadrant isolated from the side and rear compartments, while on-track the cabin is not separated due to safety concerns. Therefore, higher amplitude is expected on-track. The matching trend between on-track and wind tunnel data indicates the on-track spectral content is predominantly aeroacoustic noise, induced by the interaction of the exterior airflow with the vehicle surface and transmitted through the vehicle panels and sealing systems. With the crossbar on, the offset repeats but at the critical frequency range influenced by the crossbar effect, the amplitude offset is lower.

Figure 7 shows the contribution of the crossbar with and without the solution to the aeolian tone. The presence of two tones is seen on the unresolved crossbar, one at 192Hz and the second at 544Hz. Both tones at the same frequency band were measured at the wind tunnel. The amplitude varies according to the test method differences previously described. The occurrence of multiple tones indicate the noise mechanism acting on the crossbar is not uniquely given by the periodic pressure oscillation caused by the von Karman vortex street formation, as it occurs in flows around circular cylinders. Multiple tones indicate the presence of secondary coherent eddies and potential feedback mechanism, as it occurs in wing sections. For a circular cylinder with the same diameter as the crossbar thickness, the theoretical natural tone frequency at 120km/h given by the fundamental Strouhal number would be approximately 300Hz. Measured tones were at lower and higher frequencies than the theoretical circular cylinder tone. On the other hand, for a NACA0012 wing section of the same chord at 0° angle of attack, the expected primary tone would be at approximately 2100Hz for the speed of 120km/h. Therefore, the measured tones are also far from the expected frequency for a streamlined symmetric wing section profile such as the NACA0012.

The expected broadband noise contribution from the crossbar with the solution applied was not observed with interior measurements on-track (Figure 7.A) and barely observed at the wind tunnel (Figure 7.B). Due to this fact and in order to better investigate the tonal noise, the acoustic pressure was measured at the exterior of the vehicle, 300mm above the crossbar, in both test track (Figure 8.A) and wind tunnel (Figure 8.B). The peak tone frequencies are the same as measured with interior microphones, but the spectral behavior is considerably different and reveals critical information. In opposite to the interior microphone measurements, exterior noise data shows that the unresolved crossbar contribution presents a hump behavior instead of narrowband tones. The smooth hump behavior is potentially caused by the rough FFT resolution of 32Hz. Therefore, higher FFT resolutions will be further studied on the continuation of this project. The behavior of the crossbar with the applied solution shows a single narrowband tone at 928Hz and a broadband increment when compared to the no-crossbar condition. For the exterior sound pressure data, on-track results presented a good correlation in both trend and amplitude with the wind tunnel results, as it is shown in Figure 9. The background noise amplitude is higher on-track as expected due to engine and tire airborne noise, but the contribution of the unresolved and resolved crossbars is clear and comparable.

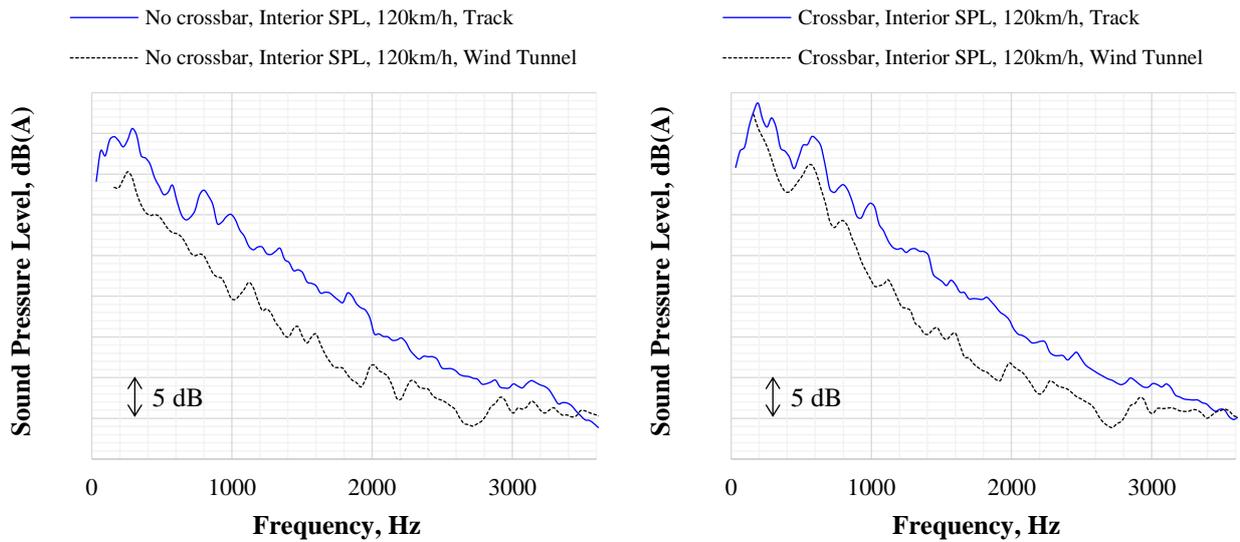


Figure 6: Comparison of the interior sound pressure level measured on-road and at the wind tunnel. No-crossbar (6.A) and with-crossbar (6.B) conditions are plot. No solution to the aeolian tone is applied.

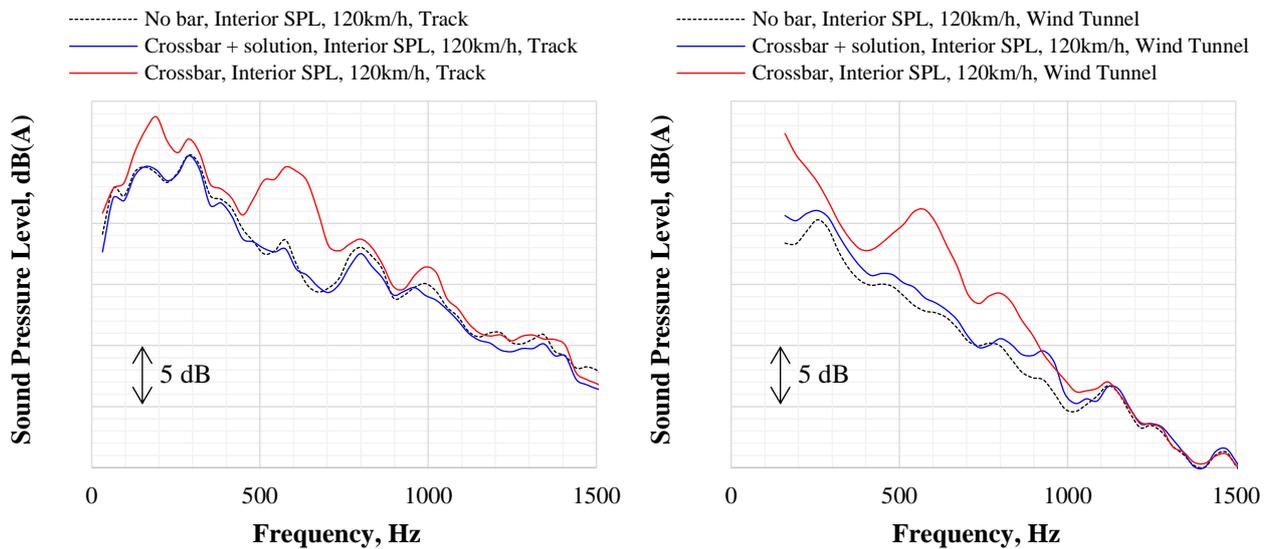


Figure 7: Interior sound pressure measured on-road (7.A) and at the wind tunnel (7.B). Wind speed: 120km/h.

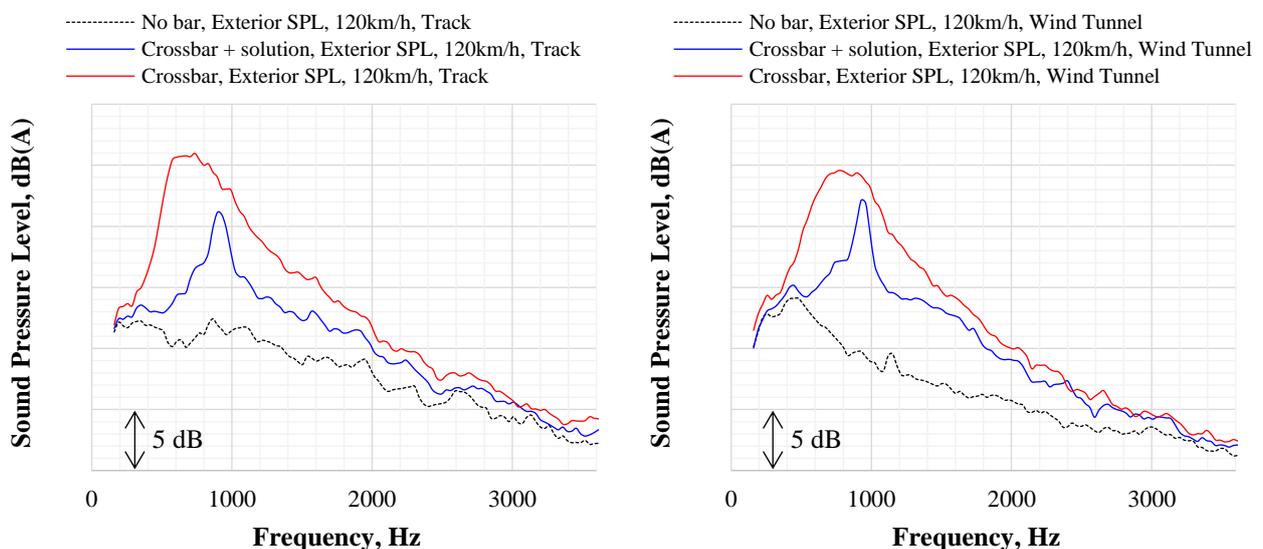


Figure 8: Exterior sound pressure measured on-road (8.A) and at the wind tunnel (8.B). Wind speed: 120km/h.

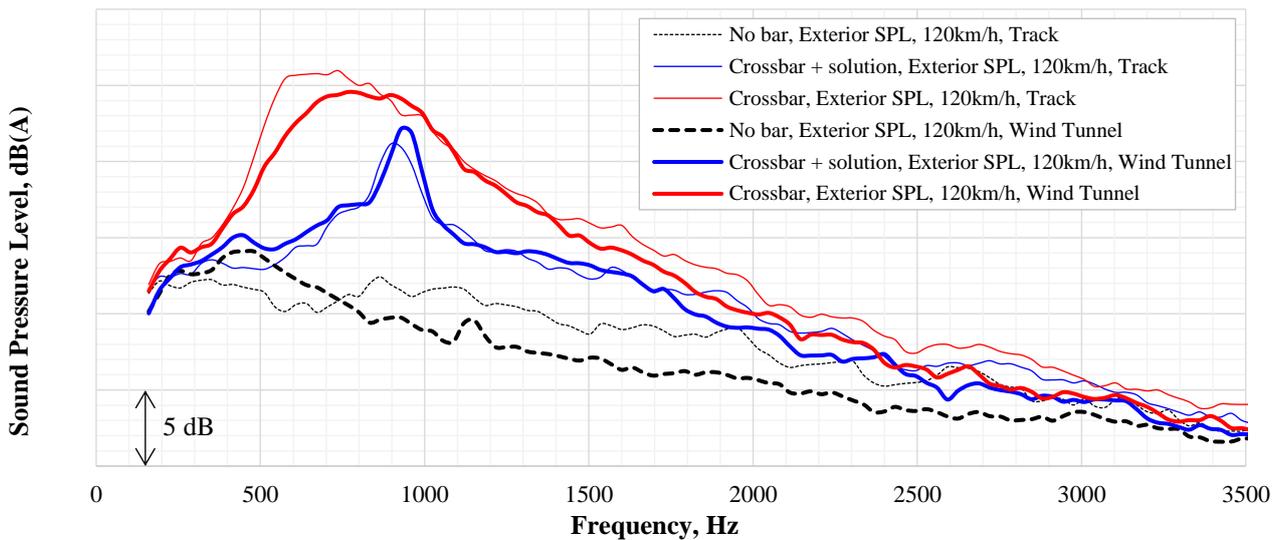


Figure 9: Comparison of exterior sound pressure level measured on-track and at the wind tunnel. Wind speed: 120km/h.

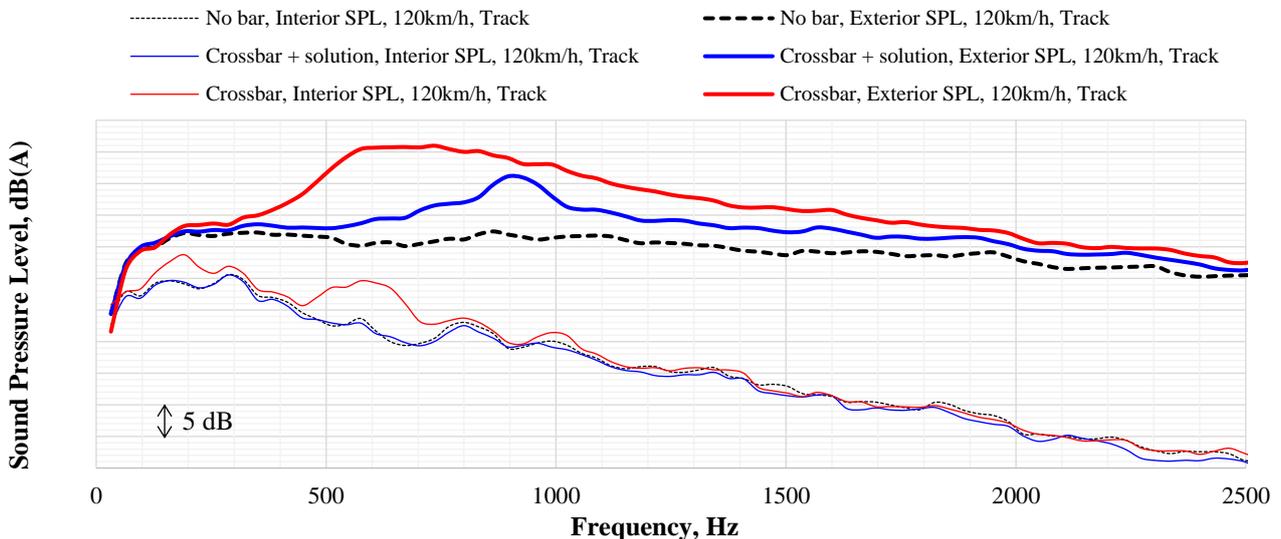


Figure 10: Comparison of interior and exterior sound pressure level measured on-track. Wind speed: 120km/h.

4. CONCLUSIONS AND FUTURE WORK

This project has compared the aeroacoustic performance from automotive roof carrier crossbars measured on road and at the wind tunnel. It was defined a proper method to investigate the noise mechanisms involved in commercial crossbar shapes to support the development of future products. Note that the solutions applied nowadays are mostly empirical and a deeper understanding of the noise mechanisms involved in typical crossbar shapes is of industry interest.

The measurement of the exterior acoustic pressure on-track has demonstrated to be accurate in capturing both broad and narrowband contributions from a typical crossbar, as shown on Figure 9. Interior sound pressure level measurements are greatly influenced by the transmission paths and have demonstrated to mask the actual aeroacoustic behavior of the crossbar, as shown in Figure 10. Therefore, measurements based on exterior sound pressure method will be adopted on the continuation of this project, and further investigation on the noise mechanisms and solutions to the aeolian tone is intended to be performed using on-track data.

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