

Investigations of the Influence of Lower Frequency Aerodynamic Noise on Interior Cruise and Exterior Pass-By Sound Levels

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ABSTRACT

The results of a series of tests were performed that are used to investigate the contribution of aerodynamic noise to lower frequency passenger car interior and exterior cruise noise levels. Wind tunnel measurements were used to isolate aerodynamic noise from tire-pavement and engine noise and to indicate that the vehicle underbody is a significant source region for both interior and exterior noise. Comparing interior on-road measurements to the wind tunnel results, it was found that aerodynamic noise was slightly less than an equal contributor to cruise noise averaging 4.8 dB lower than the road levels between 50 and 400 Hz at a speed of 80 km/h. At 140 km/h, the difference dropped to 2.3 dB indicating that the aerodynamic noise was the major contributor. For exterior pass-by, aerodynamic noise levels were found to account for almost all of the noise measured during coast-by conditions in the frequency range from 50 to 400 Hz at 97 km/h. This finding was substantiated by additional pass-by testing using different tires on a variety of pavements. It was further found that aerodynamic noise was likely a partial contributor to pass-by noise levels at vehicle speeds as low as 56 km/h. These influences were also indicated by comparing tire-pavement source levels measured on-board to the overall cruise and coast pass-by levels. Although the influence of aerodynamic noise will vary with tire design, vehicle design, pavement, and vehicle speed, this paper should provide motivation for considering it in both predicting and reducing interior and exterior noise.

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INTRODUCTION

Exterior and interior motor vehicle noise is generally lumped into the three broad categories of powertrain, tire/pavement, and aerodynamic noise. In terms of vehicle noise development, it was often desired to isolate the contributions of each of these in order to develop subsystem specifications. These specifications then "roll-up" into total system noise level targets for both interior and exterior noise. Subsystems are typically isolated by either operating the vehicle at a condition that emphasizes one contribution relative to the others, such as low speed, full throttle acceleration to isolate powertrain noise, or using laboratory facilities such as chassis dynamometers or wind tunnels. These methods do however have their limitations as the operating condition of interest may actually be a blend of contributions, such as 80 km/h cruise noise which is often a blend of all three noise categories. Further, the use of laboratory facilities can create ambiguities relative to the simulation of actual on-road noise production. A good example of this latter point is indoor pass-by

dynamometer facilities in which powertrain noise is emphasized, however it is not totally isolated from the typically unrealistic noise generated by the tires in contact with the road wheel surface.

For the specific case of noise for light vehicle cruise conditions, isolating the powertrain noise contribution is somewhat straightforward as interior or exterior noise can be measured under cruise or coast conditions. Once this is achieved, it is generally considered that tire/pavement noise is the sole remaining contributor, at least up to speeds around 80 km/h on an overall A-weighted level basis¹. For interior noise, the "cross-over" between tire/pavement noise and aerodynamically generated noise may actually begin in the 80 km/h speed range depending on the vehicle, tires, and pavement. For exterior noise, based on recent research comparing on-board sound intensity measurements of exterior tire/pavement noise source levels to cruise/coast pass-by it appears that this cross-over actually occurs at lower speeds, at least for frequencies of 400 Hz and below and at

2000 Hz and above². Although the contribution of these frequency regions are only minor contributors to overall A-weighted cruise pass-by levels, they are of interest given the regulatory emphasis on cruise conditions in the proposed revisions to ISO 362 pass-by noise procedure and the regulatory requirements placed on tire noise as measured under cruise. The exterior noise generated under cruise is also of interest in determining for the load cases for predicting interior noise contributions with tools such as Statistical Energy Analysis.

In order to investigate the lower frequency contributions to interior and exterior noise, a series of wind tunnel, test track, tire noise source level measurements were analyzed. The wind tunnel tests included both interior and exterior measurements for comparison to test track interior, exterior pass-by, and tire/pavement noise source level data. As aerodynamic noise generated by vehicle underbodies is documented and reported in the literature^{3,4,5}, it was a focal point of much of this investigation, particularly for frequencies below 500 Hz. This paper reports the analysis of these data and the resultant findings more extensively as the pass-by data was analyzed in more extensively previously⁶.

DESCRIPTION OF MEASUREMENTS

INTERIOR DATA

Interior noise was measured both in the wind tunnel and on-road. In the wind tunnel, measurements were made in right front and rear and left front and rear seating positions. A single pressure response microphone was located in the center of the seating position with the microphone diaphragm 61 cm above the seat cushion. For some conditions, the four sections of the vehicle interior were isolated from each other by layers of convoluted foam. For the measurements to compare with on-road data, the foam was removed and only the right front and left rear seating positions were measured. The wind tunnel was full-scale aeroacoustic facility designed for low background noise with a three-quarter open jet configuration lined with sound absorbing treatment. The on-road measurements were conducted on fine texture, smooth hot mix asphalt pavement (HMA). The measurements were conducted primarily at 80 and 140 km/h. The output of the microphones was analyzed into sound pressure levels of either one-third octave band levels or constant width bands of 32 Hz.

EXTERIOR DATA

Exterior noise was also measured both in the wind tunnel and on a test track. These included both pass-by and sound intensity measurements made near the tire contact patch. For the vehicle passby measurements, the distance between the centerline of travel and the microphone was 7.5m as specified in the ISO 362 procedure. However, the microphone height was set to be 1.5m above the height of the pavement to be more typical of such measurements performed in the US. To

collect overall passby sound pressure levels a Larson Davis Model 820 sound level meter (SLM) was used at the track. The acoustic signals from the SLM were captured on a Sony LCD-100 two-channel digital audio tape recorder and these were used later to determine maximum passby level in one-third octave bands with a Larson Davis 2900 dual-channel real time analyzer using an one-eighth second exponential averaging time. Multiple runs were made for each test condition and those falling within a ± 1.6 km/h window about the nominal test speed were averaged together. Vehicle speed was measured with a calibrated radar gun during the passbys. A photograph showing a typical passby test set-up is provided in Fig. 1. The test vehicle was 2006 Pontiac Grand Prix. The passby tests were performed with the vehicle operated in a cruise condition with the transmission in drive producing the lowest possible engine speed and with the vehicle coasting by with the transmission in neutral and the engine at idle. In the wind tunnel, "pass-by" measurements were made using a 12.5mm ($\frac{1}{2}$ ") microphone and preamplifier located out of the airflow 1.5m above the tunnel floor and 7.5m to the side of the stationary vehicle. In the wind tunnel tests, a variety of production test cars were used.



Figure 3. Passby measurement setup at S4

The measurements of tire noise source levels were made using the on-board sound intensity method (OBSI) performed following the American Association of State Highway Transportation Officials (AASHTO) procedure⁷ that parallels a procedure currently underdevelopment by SAE. The OBSI probe consisted of two $\frac{1}{2}$ " (12.5mm) G.R.A.S. phased matched condenser microphones installed on Larson Davis $\frac{1}{2}$ " (12.5mm) Model PRM900C microphone preamplifiers. The microphones were used in a "side-by-side" configuration with a 16mm spacing of the microphones. The probe was oriented such that its sensitive axis (a line perpendicular to the length of microphones/pre-amplifiers and determined by the line through the microphones) was pointed toward the tire sidewall (Fig. 2). Prior to the measurements, the microphones

were protected from airflow using a spherical foam windscreen. Measurements were made with the probe 75mm above the pavement, 100mm out from the tire sidewall, and at two locations, opposite the leading edge of the tire contact patch and opposite the trailing edge. These positions were measured separately with the probe re-positioned as necessary. The sound pressure signals from the two microphones went directly into the LD 2900 analyzer and the sound intensity level was produced in 1/3 octave bands in real time. The signals were also captured on the DAT recorder. Sound intensity levels from each probe position were averaged for typically three repeat runs and then the levels for the two positions were averaged to yield a single spectrum for each test condition.



Figure 2. On-board sound intensity tire noise measurement fixture on test vehicle shown without spherical windscreen over the side-by-side microphone pair of the intensity probe

The wind tunnel measurements paralleled those discussed above. Sound intensity and sound pressure levels were measured at the OBSI positions in the tunnel with the only source of noise being that generated by the airflow. In addition to the conventional fixturing shown in [Figure 2](#), an “idea” probe was also used to capture noise without any contribution for the fixture itself ([Figure 3](#)).

The exterior on-road testing was conducted at the National Center for Asphalt Technology (NCAT) test track facility in Opelika, Alabama. The NCAT track consists of 48 hot mix asphalt (HMA) test sections, typically about 200 ft in length over a 1.7-mile oval. These pavements provide a range of surface roughness, construction type, and porosity. The track is sufficiently wide that passby measurements were made with the sound propagating over HMA at a distance of 7.5m. For the testing, four pavements were selected that, based on previous measurements, produced a large range in

noise level. Three of the sites were essentially identical in geometry with different pavements. These are identified as test section S1, S4, and S5. These sections were flat and level, with the passby microphone located just off the edge of asphalt. The pavement in section S1 was a medium texture stone mastic asphalt, 46mm thick and non-porous. Section S4 was an open graded asphalt pavement of coarse texture, 25mm thick and porous. Section S5 was asphalt “Superpave” construction of fine texture, 38mm thick, and non-porous. The geometry of the fourth test site (section W3) was somewhat more complex. This test section was located on a banked corner of the track. At this location, although the surface is sloped, it remains visually flat across its width. This section was chosen especially for its unique surface. The pavement consists of relatively fine aggregate HMA with transverse grooves cut into the surface. This traverse texture generates sounds that are similar to concrete counterparts with aggressive transverse texturing or grooving. Photographs of each of the test surfaces are provided in [Figure 4](#).



Figure 3. Lower noise “ideal” sound intensity probe used in wind tunnel testing located at the trailing edge OBSI probe location

The original intent was to conduct the testing for all sections at 56, 72, and 97 km/h consistent with those speeds specified in the AASHTO provisional OBSI test procedure⁶. This was readily achievable for sections S1, S4, and S5. For section W3, it was found that 97 km/h could not be safely maintained through the banked corner without putting additional side force on the tires. As a result, the upper speed at this site was limited to 88 km/h.