

The Effects of Unsteady On-Road Flow Conditions on Cabin Noise: Spectral and Geometric Dependence

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ABSTRACT

The in-cabin sound pressure level response of a vehicle in yawed wind conditions can differ significantly between the smooth flow conditions of the aeroacoustic wind tunnel and the higher turbulence, transient flow conditions experienced on the road. Previous research has shown that under low turbulence conditions there is close agreement between the variation with yaw of in-cabin sound pressure level on the road and in the wind tunnel. However, under transient conditions, sound pressure levels on the road were found to show a smaller increase due to yaw than predicted by the wind tunnel, specifically near the leeward sideglass region.

The research presented here investigates the links between transient flow and aeroacoustics. The effect of small geometry changes upon the aeroacoustic response of the vehicle has been investigated. It was found that sideglass pressures showed close agreement at all turbulence levels while surface sound pressure levels also showed similar behaviour under a wide range of on-road flow conditions. While the overall sideglass sound pressure level changed under the various yaw conditions, the change in shape of the frequency spectrum was less significant.

Geometry changes made to a base vehicle reduced the sensitivity of the in-cabin noise to on-road turbulence, showing that shape-change can modify sensitivity to on-road turbulence.

INTRODUCTION

At higher vehicle speeds, aerodynamic noise tends to dominate the overall noise level inside the passenger compartment of a vehicle. At speeds that are commonly attained on a highway, aerodynamic noise dominates, as shown by Hucho (1998) [1] and Blumrich (2009) [2]. As the level of tyre, engine and powertrain noise have reduced as vehicles have developed, the relative importance of aerodynamic noise has increased. This is particularly the case in the luxury vehicle sector, where these other sources are more isolated from the passengers. In addition, primary noise generation sources such as the A-pillar region, Watkins (1999) [3], and door mirrors, George (1990) [4], tend to be located very close to the driver and therefore the driver is very sensitive to noise produced in these regions. With the emergence of new technologies such as electric vehicles, aerodynamic noise will become increasingly important owing to the consequent reduction in engine noise.

As the automotive industry develops vehicles with increased fuel efficiency and reduced emissions, the overall level of comfort inside a vehicle remains important as a differentiator between vehicles. Cabin noise is an important component of the passenger experience inside a vehicle and it follows that aerodynamic noise is therefore linked to how a customer perceives the overall levels of comfort and quality of a particular vehicle.

Being able to predict how a vehicle will behave in the transient, turbulent conditions experienced on-road during the development of a vehicle is important, since changes in

design due to yaw and turbulence sensitivity can become very costly later in the design process. Typically, aerodynamic noise development work takes place in an aeroacoustically treated wind tunnel that, in the majority of cases, has flows that are both spatially and temporally invariant. The noise generated in these steady flows are correspondingly steady and therefore do not fully capture the vehicle's response to the unsteady flows typically experienced on-road. Turbulence generation systems have been installed in aeroacoustic wind tunnels as shown Cogotti (2003, 2005) [5] [6], which can be used to assess cabin noise under these turbulent conditions. Passive systems, such as those placing a vehicle upstream of the test section as described by Saunders and Mansour (2000) [7], Watkins et al. (2001) [8], Cogotti (2003) [5] amongst others, tend to simulate only a limited range of conditions that a vehicle can experience while traversing the on-road environment. Active methods allow a wider range of conditions to be simulated and as these methods improve, better comparisons can be made between the on-road environment and the aeroacoustic wind tunnel. However, the full range of conditions that a vehicle can experience, as investigated by Wordley and Saunders (2008, 2009) [9] [10], are still not possible to fully simulate.

Alternatively, simulation techniques such as those described by Krampol et al. (2009) [11] can avoid the use of such turbulent simulation devices. Using these techniques, cabin noise is recorded under a range of flow velocities and yaw angles and blended together based on typical on-road conditions. However, these techniques are currently limited by the assumption that the cabin noise response is quasi-steady and unaffected by the faster transient conditions experienced on-road.

A small number of studies have taken place including those by Watkins et al. (2001) [8] and Lindener et al. (2007) [12], comparing the cabin noise response of a vehicle on-road and in the aeroacoustic wind tunnel. Previous work by Oettle et al. (2010) [13] has shown that on-road, the cabin noise can vary in level from that predicted by the aeroacoustic wind tunnel. It was found that the variation of in-cabin sound pressure level (SPL) with yaw in the wind tunnel was in close agreement with on-road data at low lateral turbulence intensities. However, at higher lateral turbulence intensity there was a discrepancy between the wind tunnel and on-road sound pressure level, specifically to noise levels near the leeward sideglass. Sound pressure levels in this area were shown to have a smaller increase due to yaw than predicted by the aeroacoustic wind tunnel, indicating that transient flows around the leeward side of the vehicle may not have time to fully develop to their steady, high SPL condition.

Lawson et al. (2007, 2008) [14] [15] investigated differences in flow structures of a vehicle on-road and in the wind tunnel, particularly in the A-pillar region. This paper aims to investigate this further by assessing how flow structures and

noise generation around the sideglass region are affected by variations in yaw angle and turbulence on-road. In addition to how the overall level of the cabin noise varies under on-road conditions, changes to the frequency content of the cabin noise were assessed. Finally, the effects of minor geometry changes to the vehicle were evaluated within the on-road environment.

EXPERIMENTAL METHOD

TEST VEHICLE AND BODY MODIFICATIONS

A European luxury saloon was used as the test vehicle, shown in Figure 1. The coordinate system that is used throughout the paper is shown in Figure 2, when viewed from above the vehicle. The probe is aligned with the vehicle throughout the experimentation.

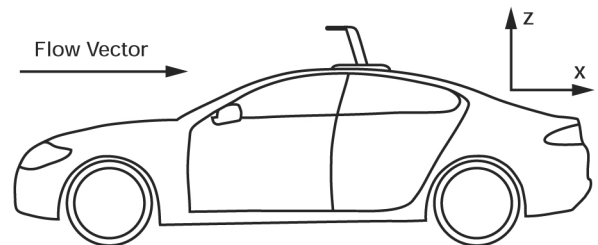


Figure 1. Test vehicle showing location of probe

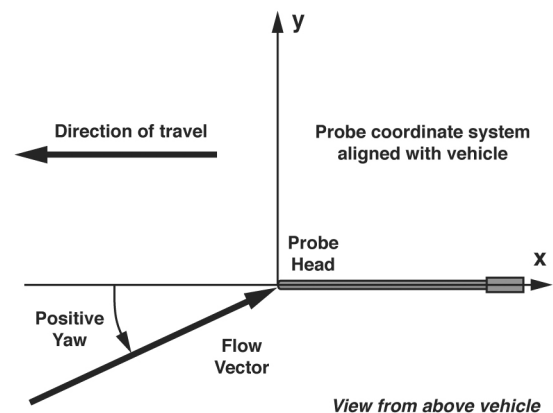
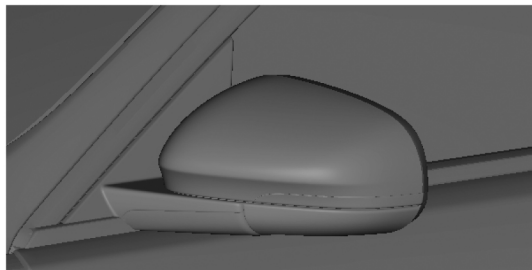


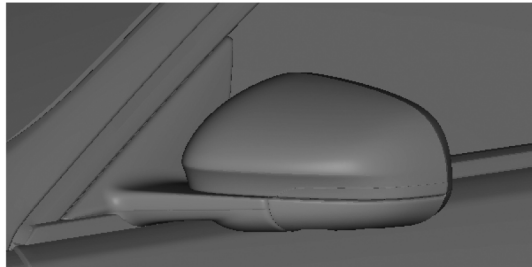
Figure 2. Probe and vehicle coordinate system

The base vehicle was the same as used in previous work described by Oettle et al. (2010) [13], with modifications made to both the door mirror housing and bonnet. The stems of the door mirrors were modified to improve subjective cabin noise performance, as shown in Figure 3. To reduce the effect of the windscreen wipers on noise generation, a modification to the rear lip of the bonnet was also tested. Such a deflector to reduce the effect of the windscreen wipers on the cabin noise is described by Zaccariotto et al. [16]. Rapid-prototype material sections were used to increase the

height of the bonnet lip so that a larger proportion of the wipers were shielded from the oncoming flow. The sections were blended into the existing contours of the bonnet using modelling clay and secured using adhesive tape. The resulting bonnet kicker increased the height of the rear lip and 'power bulge' of the bonnet by approximately 15 mm, terminating at the trailing edge with a vertical face. This is shown in [Figure 4](#), with a summary of the geometry modifications shown in [Table 1](#).



(a). Geometry 1



(b). Geometries 2 and 3

Figure 3. Details of mirror modifications



Figure 4. Geometry 3 bonnet kicker

Table 1. Summary of geometry modifications and naming scheme

Name	Description
Geometry 1G	Base vehicle
Geometry 2G	As Geometry 1G, but with modified door mirror housing
Geometry 2	As Geometry 2G, but with surface microphones and Perspex sideglass for pressure measurements
Geometry 3G	As Geometry 2G, but with addition of bonnet kicker
Geometry 3	As Geometry 3G, but with surface microphones and Perspex sideglass for pressure measurements

FLOW MEASUREMENT

To measure the flow over the vehicle, a roof-mounted 5-hole probe was used. The probe was manufactured and calibrated in isolation using facilities at Durham University. Yaw angles and other quantities reported are therefore the actual values at the probe location. This approach avoids embedding the steady state response of the vehicle (for example, a local velocity increase at the probe) in the probe calibration. This is important since this investigation concerns the comparison between the aerodynamic response of the vehicle under steady state and transient conditions. Positioning the probe ahead of the vehicle, such as in the work by Wordley and Saunders (2008, 2009) [9] [10], would reduce the influence of the vehicle's body on the flow measurements, but would alter the flow around the vehicle. The small size of the probe head is important, since it is this size that limits the response of the probe. Since this paper is concerned about measuring the response of the vehicle to oncoming transient conditions, it is necessary for the probe to be smaller than the vehicle to have a flat response to these conditions in situations where the vehicle may not.

Five SensorTechnics HCLA12X5DB pressure transducers were used to measure the probe pressures. These measure differential pressure and have a range of ± 12.5 mbar. The transducers were packaged into a single enclosure with a common reference and located within the probe mounting. The reference port was connected via a PVC tube to a location in the trunk of the vehicle. The probe mounting was attached to the roof of the vehicle magnetically. Wind tunnel testing confirmed that the induced noise of the probe was small when measured from inside the vehicle.

The probe tip was positioned approximately 320 mm above the vehicle's roofline, and approximately 70 mm in front of the B-pillar, as shown in [Figure 1](#). This position was consistent for each of the on-road tests.

To measure the pressure distribution around the A-pillar region, a Perspex sideglass of the same size as the original glass was used. This was positioned on the driver's side (front right) of the vehicle. The exterior pressure was measured at ten locations as shown in [Figure 5](#). Each of these locations were drilled and 10 mm lengths of 1.24 mm OD tubing bonded in position, ensuring the outer surface of the sideglass remained smooth. The tubing inserts were connected to ten SensorTechnics HCLA12X5DB pressure transducers located inside the cabin via PVC tubing. Pressures were measured relative to trunk pressure, although pressure coefficients were defined based on vehicle velocity and static pressure measured at the probe tip.

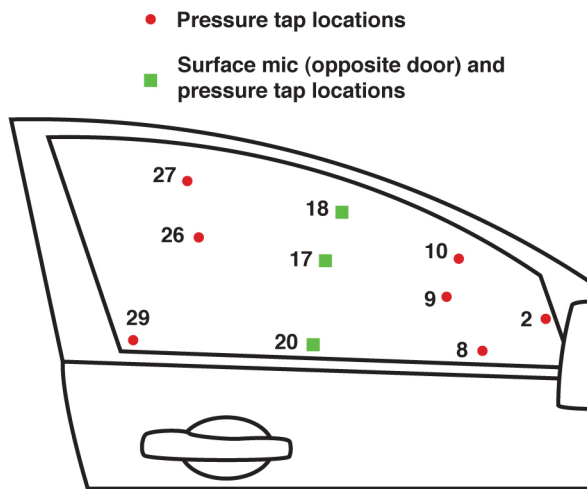


Figure 5. Location of pressure tapplings and surface microphones

A probe and tubing transfer function correction was applied, for magnitude and phase, to all on-road data for both the roof mounted five-hole probe and the sideglass pressure tapplings. This is described by Irwin et al. (1979) [16] and developed by Sims-Williams and Dominy (1998) [18]. Similar examples of its application are shown by Lawson et al. (2007) [14]. With the probe and remote transducers used in the investigation, this approach allows a frequency response in excess of 500 Hz. This significantly exceeds the required response for this application, since the energy contained within higher frequencies is low (three orders of magnitude lower at 500 Hz when compared to 1 Hz), as shown by Wordley (2009) [10]. The higher frequency fluctuations contained in the wind are also correspondingly small and are therefore not correlated over the scale of the vehicle.

DATA ACQUISITION

To log the output from the pressure transducers, a National Instruments NIDAQmx USB-6218 data logger was used. This was controlled by a laptop running control software developed at Durham University. Data were also received from a Bluetooth GPS device that was simultaneously logged

with the pressure transducer data from the data logger using the same control software. The GPS data included details of the velocity and heading of the vehicle, in addition to information on the location of the vehicle and time of the experiment. The pressure transducer data were logged in sets of 16384 points at 500 Hz, therefore giving a logging duration of 32.768 s. This logging time was considered suitable to capture the transient nature of the on-road environment. To reduce aliasing, the signal from each of the pressure transducers was passed through a 250 Hz second-order low-pass filter.

The data logging system included a number of features to assist with the correlation between the data and the on-road environment, as well as the in-vehicle control of the system. An LED display was mounted on the dashboard of the vehicle, providing the driver with information on the logging status, GPS signal and run number. A video camera also recorded on-road events to further assist correlation between the external environment and the flow and noise data. To synchronise both the flow and audio logging systems, a combined external trigger was used to start both systems from within the vehicle. A schematic of the entire logging system is shown in [Figure 6](#).

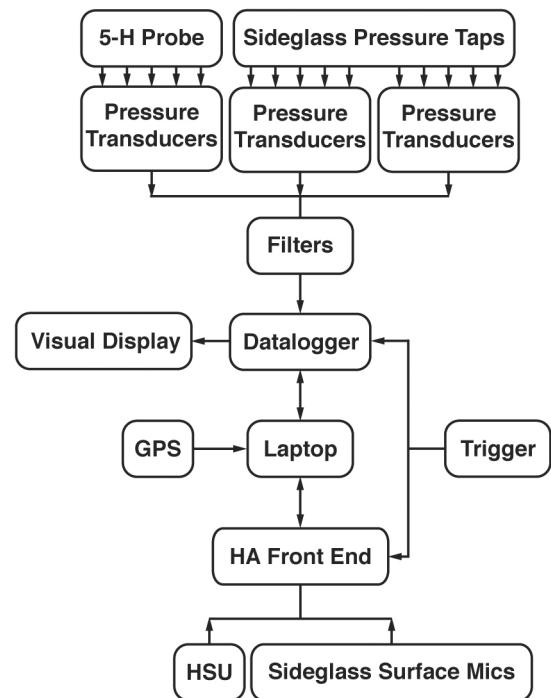


Figure 6. Schematic of logging system

NOISE MEASUREMENT

A Head Acoustics HSU (head and shoulder unit, or acoustic head) with torso was used to record the cabin noise. The HSU was positioned on the front left (passenger) seat of the vehicle and fixed securely to prevent any additional noise generation.