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# Assessing the Aeroacoustic Response of a Vehicle to Transient Flow Conditions from the Perspective of a Vehicle Occupant

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## ABSTRACT

On-road, a vehicle experiences unsteady flow conditions due to turbulence in the natural wind, moving through the unsteady wakes of other road vehicles and travelling through the stationary wakes generated by roadside obstacles. Separated flow structures in the sideglass region of a vehicle are particularly sensitive to unsteadiness in the onset flow. These regions are also areas where strong aeroacoustic effects can exist, in a region close to the passengers of a vehicle. The resulting aeroacoustic response to unsteadiness can lead to fluctuations and modulation at frequencies that a passenger is particularly sensitive towards. Results presented by this paper combine on-road measurement campaigns using instrumented vehicles in a range of different wind environments and aeroacoustic wind tunnel tests.

A new cabin noise simulation technique was developed to predict the time-varying wind noise in a vehicle using the cabin noise measured in the steady environment of the wind tunnel, and a record of the unsteady onset conditions on the road, considering each third-octave band individually. The simulated cabin noise predicted using this quasi-steady technique was compared against direct on-road cabin noise measurements recorded under the same flow conditions to assess the response of the vehicle to oncoming flow unsteadiness.

The technique predicted the modulation of the wind noise under unsteady on-road conditions with good fidelity. This is because the cabin noise response to oncoming flow unsteadiness remained generally quasi-steady up to fluctuation frequencies of approximately 2 to 5 Hz, with fluctuations at higher scales having a progressively smaller impact, and because most of the onset flow fluctuation energy on the road occurs at frequencies below this threshold.

The relative impact of the baseline level of cabin noise and the sensitivity of the cabin noise to changes in yaw angle were assessed in terms of occupant perception and this highlighted the importance of modulation. This can provide guidance when assessing the on-road wind noise performance of vehicle geometry modifications and of different vehicles.

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## INTRODUCTION

On-road, a vehicle experiences unsteady flow conditions due to turbulence in the natural wind, moving through the unsteady wakes of other road vehicles and travelling through the stationary wakes generated by roadside obstacles. These various sources of oncoming flow unsteadiness and their effects have been investigated by various researchers including [1, 2, 3, 4, 5, 6] and are summarised by [7]. Previous work on unsteady on-road effects on aeroacoustics has been published by [8, 9, 10, 11, 12, 13]. Separated flow structures in the sideglass region of a vehicle are particularly sensitive to unsteadiness in the onset flow. These regions are also areas

where strong aeroacoustic effects can exist, in a region close to the passengers of a vehicle. The resulting aeroacoustic response to unsteadiness can lead to fluctuations and modulation at frequencies that a passenger is particularly sensitive towards.

Previous research [11] investigated the surface pressure response of the front sideglass region to oncoming flow unsteadiness. This found that, with the exception of the region closest to the A-pillar, the pressures behaved in a quasi-steady manner up to 2-10 Hz. Beyond this, higher frequency unsteady fluctuations had a progressively reduced impact on the

sideglass pressures. Therefore, with knowledge of the surface pressure profiles measured under a range of steady conditions (for instance, in the wind tunnel), using the instantaneous oncoming flow yaw angle measured on-road, the surface pressure profile could be predicted.

Deviations to the quasi-steady response in the sideglass surface pressure distribution from that predicted under steady-state conditions were found to occur, isolated particularly to the region nearest the A-pillar under leeward flow conditions.

This work was developed [10] to investigate what impact these unsteady effects have on the aeroacoustic noise inside the passenger compartment. Using a quasi-steady cabin noise simulation technique, based on modulating the overall level of cabin noise as recorded under the steady conditions of the aeroacoustic wind tunnel, evidence of a quasi-steady cabin noise response up to 2-5 Hz was found to occur.

This work extends that investigation, using a refined cabin noise simulation technique to determine what impact unsteady effects (particularly the non-quasi-steady surface pressure behaviour in the A-pillar region) have on the aeroacoustic noise inside the passenger compartment.

In addition, one key advantage of the simulation technique is that it allows unsteady cabin noise to be produced, listened to and subjectively assessed through jury testing. Using this, the relative impact of cabin noise modulation as perceived by a vehicle occupant due to unsteady oncoming flow conditions is also assessed.

## EXPERIMENTAL DATA COLLECTION METHODS

The experimental data collected were used for two purposes. Firstly, to generate the simulated aeroacoustic cabin noise, data were recorded under the steady flow conditions of the AWT to capture the steady-state response of the vehicle. Unsteady oncoming flow conditions under a range of conditions were also measured on-road. Using the method described later in the paper, these two sets of data were combined to generate the unsteady aeroacoustic cabin noise simulation as would be heard on-road under the measured flow conditions.

In addition, the cabin noise was also recorded on-road under the same unsteady flow conditions, and these data were used to compare with the predicted cabin noise to compare and validate the simulation.

The following sections outline the instrumentation and measurement techniques used to collect the data required for both the cabin noise simulation and its validation.

### Test Vehicle

A vehicle typical of a European luxury sedan (saloon) was used as the test vehicle, shown in [Figure 1](#) and was the same model as used in the previous research of [14] incorporating [10,11,12,13]. As shown, a probe was mounted on the roof of the vehicle for the measurement of instantaneous flow conditions.

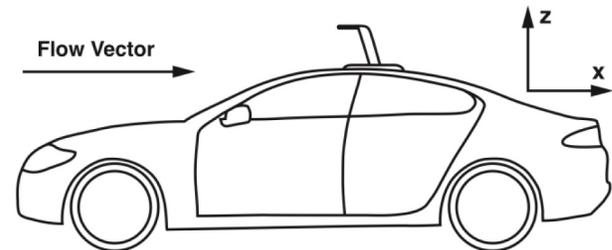


Figure 1. Test vehicle showing location of probe

### Roof-Mounted Probe

To measure the oncoming on-road wind environment as experienced by the vehicle, a roof-mounted 5-hole probe was used, as in [14]. 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](#). The probe was manufactured and calibrated in isolation using facilities at Durham University. Five SensorTechnics HCLA12X5DB pressure transducers were used to measure the probe pressures. These measure differential pressure and have a range of  $\pm 12.5$  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 boot of the vehicle. The probe mounting was attached to the roof of the vehicle magnetically.

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 tapings. This is described by [15] and implemented for probe measurements here as described by [16]. With the probe and remote transducers used in the investigation, this approach allows a frequency response in excess of 500 Hz, significantly exceeding the required response for this application.

Any probe installation location will be a compromise between measuring the incoming flow that the vehicles sees, minimizing the influence of the probe on the flow around the vehicle, and minimizing the influence of the vehicle on the flow at the probe. It was important for the design of the probe mounting not to have a significant impact on the flow at the probe tip or to affect flow around the vehicle in either the sideglass region or in other areas that may affect the noise heard inside the cabin. In addition, it was important that the probe had a minor impact on aeroacoustic measurements.

The approach used here, positioning the probe some distance off the vehicle and using a probe calibration performed in isolation rather than in situ, means that the yaw angles and

other quantities reported are the actual values at the probe location and this is known with certainty. Steady state wind tunnel measurements show that the probe experiences a speed up of both longitudinal and lateral velocity components. This has been shown to be a good probe location for accurate measurement of yaw [14], although the yaw angle seen by the probe still becomes slightly exaggerated at higher yaw angles. While it may be tempting to “correct” for the effect of the flow around the vehicle on the probe measurement, that would assume that the flow around the vehicle in a transient condition matches that in the steady state condition. This investigation concerns the comparison between the aerodynamic response of the vehicle under steady state and transient conditions and so such an assumption would not be appropriate *a priori*.

### 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 in-house. Data were also received from a 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 32.8 s. This logging time was considered suitable to capture the transient nature of the on-road environment. To avoid aliasing, the signal from each of the pressure transducers was passed through a low-pass filter.

### Cabin Noise Measurement

A Head Acoustics binaural head with torso was used to record the cabin noise. This was positioned on the front left (passenger) seat of the vehicle and fixed securely to prevent any additional noise generation and the vehicle ventilation system was switched off during testing. The acoustic head was connected to the logging computer via a Head Acoustics frontend and controlled through the Head Acoustics HEAD Recorder software. Logging took place at 44.1 kHz. In addition to the combined trigger for both flow and audio logging systems, a 2 kHz tone was generated and silenced at the point of logging to assist synchronising the logging systems with a simultaneous video recording. Head Acoustics ArtemiS software was used to extract SPL (sound pressure level) from the audio data collected both on-road and in the wind tunnel.

### Wind Tunnel

The Pininfarina wind tunnel was used to assess the cabin noise response of the vehicle to discrete steady-state flow conditions. Instrumentation remained the same as for on-road data collection. The results reported here were obtained using a stationary ground and wheels and without the Pininfarina turbulence generation system in operation. Measurements were made at a range of turntable yaw angles from -20 degrees to +20 degrees at 2.5 degree increments. The nominal

wind tunnel velocity matched the on-road driving velocity. For the wind tunnel measurements as well as the on road measurements the yaw angles reported in the results correspond to those measured at the probe since this is what is always known with certainty, as discussed above.

## UNSTEADY WIND NOISE SIMULATION METHOD

An unsteady wind noise simulation technique was implemented that used the vehicle cabin noise measured under the steady-state conditions of the aeroacoustic wind tunnel combined with unsteady flow condition data measured by a vehicle travelling on-road. The technique built upon those introduced in [10, 11], whereby a quasi-steady approach was used to assess the surface pressure response on a vehicle front sideglass and the level of aeroacoustic broadband cabin noise fluctuations respectively.

### Broadband Modulation Approach

The broadband cabin noise approach of [10] is described using the four following steps:

### Measurement of On-Road Flow Conditions

Using the flow-measurement probe mounted on the roof of the vehicle, the instantaneous oncoming flow unsteadiness was measured under a range of wind and traffic conditions whilst travelling on highways at constant vehicle speed.

The range of oncoming flow speeds and yaw angles as measured throughout the test campaign using the roof-mounted probe are presented by [Figure 2](#) and [Figure 3](#) respectively, plotted with a normal distribution.

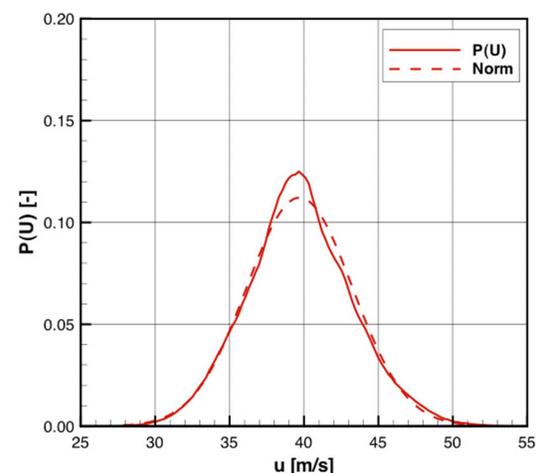


Figure 2. Probability distribution of on-road resultant flow speed

The resultant flow speed distribution of [Figure 2](#) closely follows a normal distribution, indicating that the resultant flow speed data was reasonably representative of what would be experienced under normal driving conditions, with no bias towards high or low wind conditions. In the case of the yaw angle distribution of [Figure 3](#), the bias towards zero yaw

suggests there was a greater chance for the prevailing wind direction to be aligned with the direction of travel of the vehicle. This may either be due to macro-scale weather conditions at the time of testing, or more likely due to the channelling effect of the wind as it passes along the road, for example due to embankments.

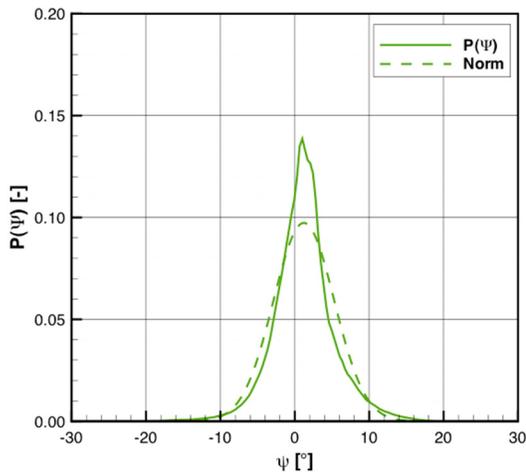


Figure 3. Probability distribution of on-road yaw angle

### Measurement of Steady-State Cabin Noise Response

The cabin noise of a vehicle was recorded in the AWT under the same nominal flow conditions (zero yaw and the same flow speed as the vehicle was travelling at on-road). In addition, the cabin noise was also recorded at the range of steady-state flow speeds and yaw angles that were experienced in the on-road environment. This provided information as to how the level of the measured cabin noise changes (modulates) when the flow conditions deviate from the zero yaw, nominal flow speed case. The resulting characteristic describing how the overall level of the cabin noise measured under the range of steady-state flow conditions is shown by Figure 4.

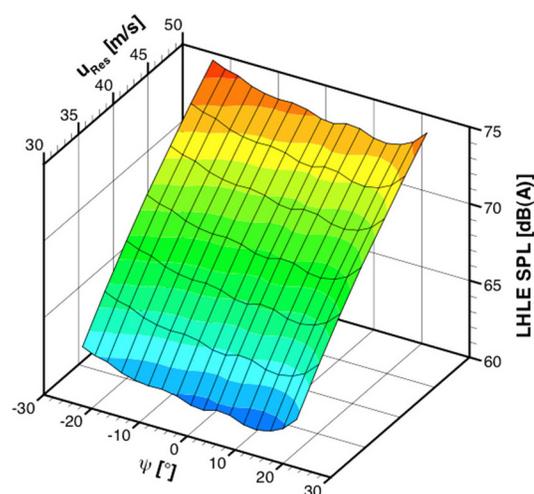


Figure 4. AWT cabin noise characteristic

### Prediction of Cabin Noise Modulation

By combining the measured flow conditions data with the steady-state cabin noise response measured in the AWT, for each instantaneous flow speed and yaw angle measured on-road the AWT-predicted cabin noise level was recorded, building up a steady-state prediction of how the cabin noise responds to the instantaneous flow conditions. This provides an instantaneous prediction of how the nominal cabin noise is modulated under a particular set of on-road flow conditions. Figure 5 depicts the resulting output when the cabin noise level recorded at the nominal flow speed and zero yaw is modulated using the steady-state cabin noise characteristic of Figure 4 and on-road measured flow conditions.

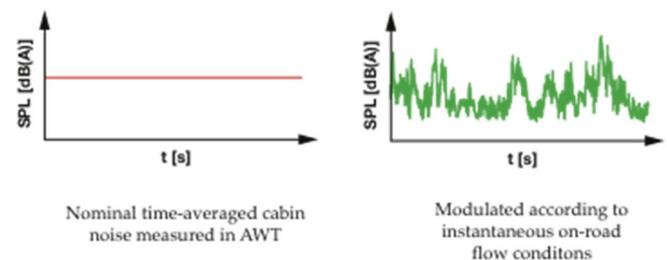


Figure 5. Cabin noise level modulation using the steady-state AWT characteristic and on-road flow conditions

### Modulation of the Recorded Steady-State Cabin Noise

The predicted cabin noise modulation was then used to modulate the level of the cabin noise recorded in the AWT under the nominal flow conditions. This technique is analogous to amplitude modulation in radio transmission, with the modulated cabin noise level of Figure 5 used as the modulation envelope of the recorded cabin noise. This is depicted in Figure 6. An audio file of the simulated wind noise was produced, allowing subjective listening studies to take place on various wind conditions and vehicle characteristics.

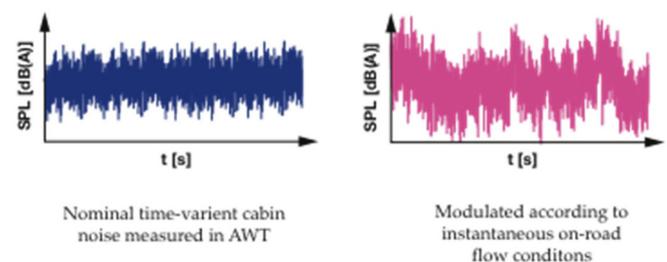


Figure 6. Cabin noise simulation through modulation of the time-variant cabin noise

### Refined Third-Octave Simulation Approach

A shortcoming of the broadband cabin noise modulation technique, noted by [10], is that the same modulation is applied to all acoustic frequencies (third-octave bands) whereas different parts of the acoustic spectrum will respond differently changes in yaw angle. Therefore a new third-octave modulation simulation

process is introduced here, as outlined in Figure 7. This allows the individual behaviour of each third-octave band to be captured, extending the broadband technique.

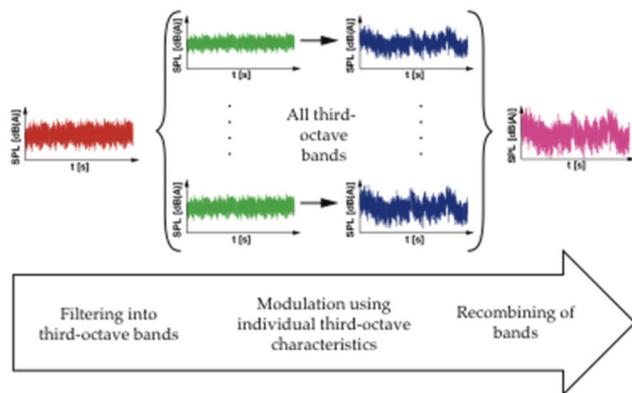


Figure 7. Cabin noise simulation through third-octave modulation

Firstly, the baseline cabin noise recorded in the AWT at zero yaw and at 36.1 m/s was filtered into separate third-octave bands. These filtered bands were then modulated based on the on-road conditions and the steady state dependence of that third-octave band on yaw and flow speed as determined from the AWT. The modulation approach was identical in principle to that of the broadband simulation approach, except applied to each third-octave band individually. Finally, each of the individual bands was then recombined to produce the overall quasi-steady cabin noise simulation.

## VALIDATION OF SIMULATION

Figure 8 and Figure 9 show the results obtained using the third-octave modulation approach and comparing these against the measured on-road data. Here, the two wind-noise dominated bands centred about 6300 Hz and 8000 Hz are presented. The simulated data contains only aeroacoustic content, whereas the on-road data also contains content from the powertrain and tyres, leading to level offsets and fluctuations due to changes in road surface. Therefore to provide an objective comparison, higher frequency content was used as a comparison, which was less corrupted by other on-road noise sources.

Overall, the third-octave modulation technique showed excellent correlation with that of the measured cabin noise, allowing replication of both the amplitude and frequency modulations experienced on road. Whilst there is a slight shift in the absolute levels between the simulated and measured signals for the 6300 Hz band, both the higher and lower frequency content appears to be very well captured. In particular, the 8000 Hz band simulation is practically indistinguishable from the measured signal in the time domain.

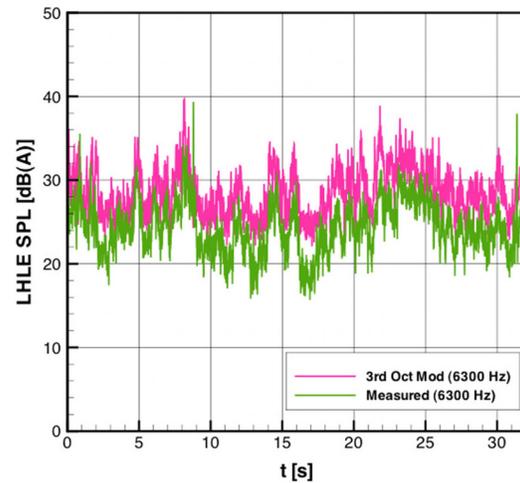


Figure 8. Temporal comparison of simulated and measured cabin noise (6300 Hz)

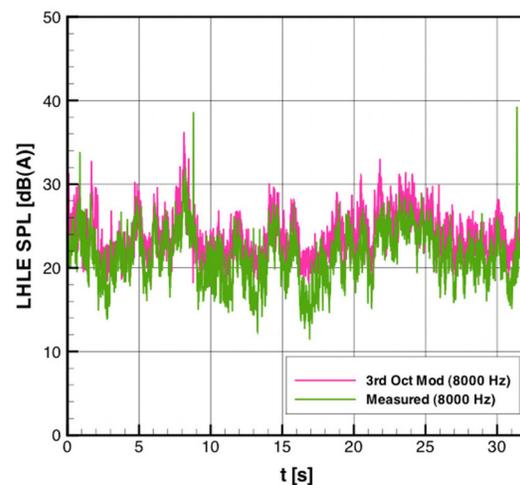


Figure 9. Temporal comparison of simulated and measured cabin noise (8000 Hz)

For a more comprehensive analysis of the nature of the vehicle response, transfer functions were once again used to compare the measured signals with those predicted using the quasi-steady technique. This was defined as the ratio of the cross-spectral density to the autospectral density of the simulated quasi-steady vehicle response [17], according to:

$$H(f) = \frac{CSD}{ASD} = \frac{G_{R_{QS}R}(f)}{G_{R_{QS}R_{QS}}(f)}$$

A diagram of the simulation and transfer function calculation process is shown by Figure 10.

This process results in a transfer function whereby a value of unity implies that the vehicle response to oncoming flow fluctuations is equal to that predicted in the steady environment of the AWT i.e. the response is quasi-steady, equivalent to an admittance of unity. A transfer function of greater than unity implies that the vehicle responds to a greater extent that

predicted by the instantaneous oncoming flow conditions alone, whilst a response of less than unity implies a response less than predicted under steady conditions.

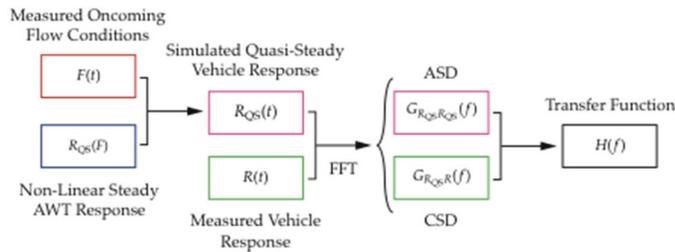


Figure 10. Method to assess the transient response of a vehicle via a transfer function approach

It has been shown, for instance by [18], that for the aerodynamic response of a vehicle, a transfer function of unity would be expected at lower frequencies for scales much greater than the vehicle, where the response can be considered to be quasi-steady. At higher frequencies, the vehicle response is no longer quasi-steady, although the higher-frequency, small-scale fluctuations much smaller than the size of the vehicle have a progressively decreasing impact on the vehicle, leading to a transfer function of less than unity. In the intermediate frequency range, scales of unsteadiness may exist that are sufficiently large and of sufficient energy to influence a vehicle, but not so large that they can be considered to be quasi-steady. This is discussed further in [7]. These effects could lead to transfer function values of greater than unity and these are sometimes associated with resonances of the vehicle suspension system in the case of vehicle forces.

The resulting transfer functions generated using the third-octave modulation process are shown by Figure 11.

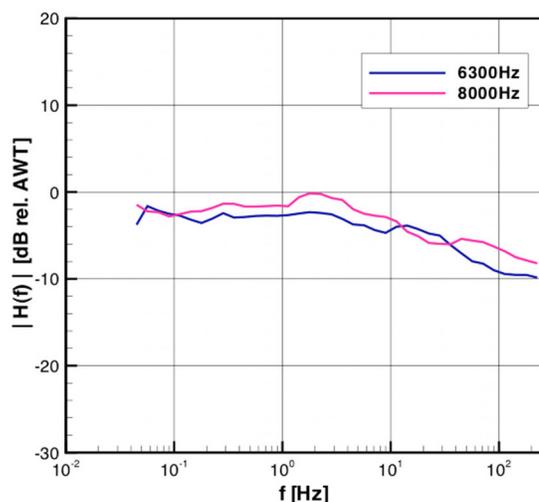


Figure 11. Transfer functions between quasi-steady predicted and on-road measured cabin noise, using third-octave modulation simulation technique

The transfer functions are presented based on dB relative to the SPL recorded under steady conditions in the AWT. Up to 2 Hz, the transfer function amplitude for the 6300 Hz and 8000 Hz frequency bands remains at a fairly constant level, with fluctuations 2 dB below those predicted by the AWT, providing strong evidence of the quasi-steady cabin noise response of the vehicle for frequencies up to 2 Hz. The 2 dB level reduction suggests that the third-octave modulation approach tends to over-estimate the amplitude of the cabin noise fluctuations. A slight overestimation of the quasi-steady predicted fluctuations may be expected, owing to the additional on-road sound sources masking the full extent of the unsteadiness-driven fluctuations. With an increase in cabin noise frequency, aeroacoustic sources increasingly dominate over the powertrain and road noise contributions. This may therefore explain the increase in transfer function amplitude for the 8000 Hz frequency band over the 6300 Hz band.

It should be noted that this technique was demonstrated using a well-developed production vehicle with no significant tonal aeroacoustic sources present. It is possible that tonal noise sources such as vortex shedding or cavity resonances may not exhibit such a quasi-steady response, since the formation of any coherent flow structures may be more sensitive to the rate of change of oncoming flow.

As expected, above 2-5 Hz, the magnitude of the transfer functions gradually decreases as the smaller fluctuations of the oncoming flow unsteadiness have a progressively reduced impact on fluctuations in noise as heard inside the cabin. With the majority of unsteady energy on-road occurring below the quasi-steady boundary of 2-5 Hz, this allows quasi-steady techniques to be used in the development of a vehicle in practise. Therefore, this indicates that the behaviour of a vehicle as assessed using steady-state techniques is likely to be sufficient in determining the front sideglass-dominated cabin noise performance as measured on-road, provided that the steady measurements are analysed appropriately with an understanding of the unsteady on-road environment.

## SUBJECTIVE JURY TESTING

A useful by-product of the simulation techniques used to assess the cabin noise response of a vehicle to unsteady flow conditions is that it provided simulated cabin noise that can be listened to and subjectively assessed. Simulated cabin noise produced using this technique provides an accurate representation of the aeroacoustic content of a vehicle's cabin noise on-road. It allows different (real or hypothetical) vehicles to be compared as if driven through identical conditions on-road.

This technique was used to subjectively assess various features of aeroacoustic cabin noise including changes to the sensitivity of cabin noise to yaw angle, the effect of overall shifts in sound pressure level and how changes in fluctuation frequency were perceived. Previous work, for instance [19], has shown that a vehicle occupant can be sensitive to

modulations in the noise heard inside the cabin. Here, results relating to the relative importance of yaw sensitivity and overall level are presented.

While the sound pressure level of cabin noise fluctuates with changes in both oncoming flow speed and yaw angle, this part of the study focussed on the sensitivity of cabin noise to yaw angle variations. This was because changes in vehicle geometry predominantly affect the yaw response, whereas the flow speed sensitivity of a vehicle is primarily driven by the dipole-dominated aeroacoustic mechanisms that do not change significantly between vehicles with similar sealing.

The on-road yaw fluctuation data was an 8 second extract of data collected during a period of strong winds. The yaw angle is predominantly negative and shows characteristics of gusting, particularly between 4 and 6 seconds and is shown in Figure 12.

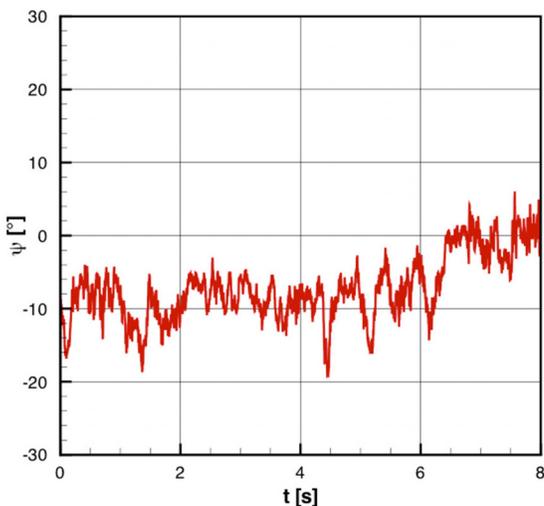


Figure 12. Yaw time history as used in subjective assessment

Using a broadband cabin noise modulation technique, the yaw time history was combined with various cabin noise characteristics to generate a simulated cabin noise time history. A number of different characteristics were used to assess both the effect of an increase in overall sound pressure level against that of an increase in yaw sensitivity, allowing the relative importance to be determined.

Two different yaw sensitivity characteristics are presented, denoted *YawSens0* and *YawSens1* and shown by Figure 13 and Figure 14. The overall shapes are idealised but the level of yaw response is representative of that of real vehicles. In addition, three steady-state sound samples were generated, unaffected by changes in yaw angle. These were the cabin noise as directly measured in the wind tunnel (denoted *AWT*); this noise sample increased in level to match the average level of the *YawSens0* characteristic (denoted *AWTAve*), and a further increase matching the maximum level of the *YawSens0* characteristic (denoted *AWTMax*).

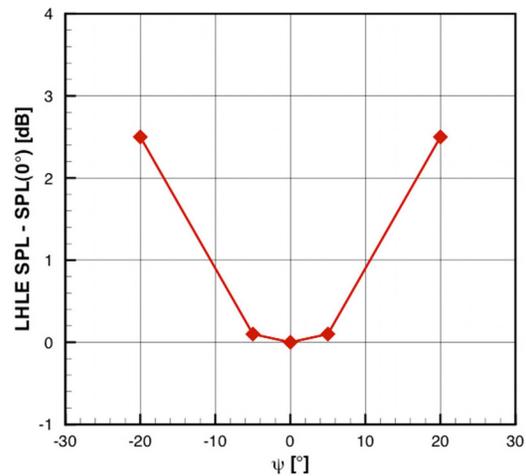


Figure 13. YawSens0 characteristic

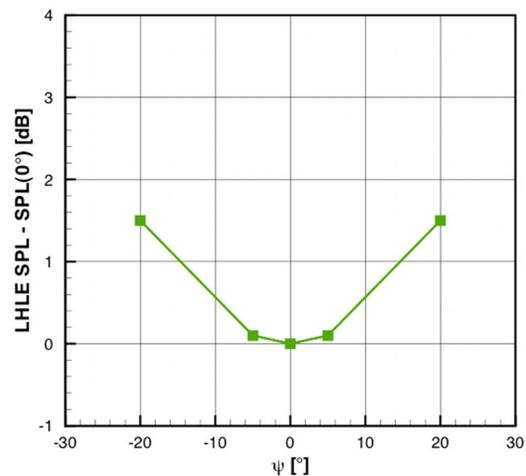


Figure 14. YawSens1 characteristic

Subjective testing took place using the ranking technique, whereby each of the resulting sound samples was given a score ( $r$ ) between 0 (most annoying) and 100 (least annoying). Once all of an individual's responses were completed, their score was then normalised such that the lowest ranked score was adjusted to 0, the highest score adjusted to 100, with the other scores linearly interpolated in between.

A total of 33 respondents were asked to assess the sound samples. To assess the quality of each of the participant's responses, the coefficient of determination  $R^2$  was calculated between their responses and the average responses of the cohort. A quality threshold was set such that respondents scoring  $R^2 < 0.9$  were rejected from the average.

The effect of yaw sensitivity on subjective cabin noise response was assessed by comparing the results obtained from the two differing yaw sensitivity characteristics and the baseline *AWT* measurement, independent of yaw. The yaw sensitivity of a vehicle can generally be altered by changing parts of a vehicle that tend to result in separated flow

structures at yaw. This includes door mirrors, windscreen wipers or features around the A-pillar. The results are compared in Figure 15.

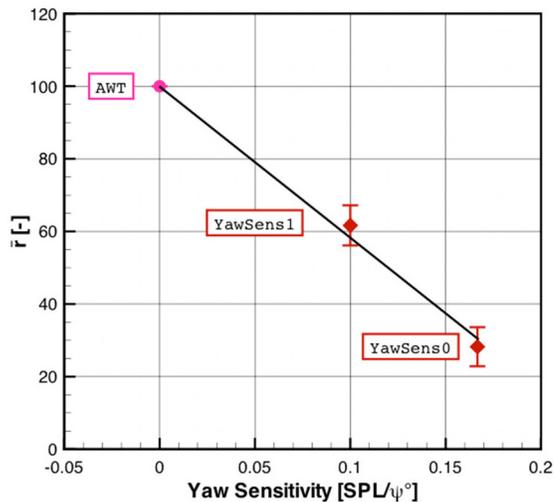


Figure 15. Effect of yaw sensitivity

The first, and perhaps most obvious, observation is that an increase in the sensitivity of cabin noise to changes in yaw angle led to a decrease in a respondent's subjective score. Therefore, a vehicle with a greater sensitivity to yaw angle would have a likelihood of reduced wind noise perceived performance on-road. By also comparing the gradient of the yaw characteristic between 5 and 20 degrees yaw, there appears to be a linear relationship between yaw sensitivity and subjective response.

Comparing the average SPL increase from the baseline cabin noise time history, as shown by Figure 16 the expected relationship between SPL (L) and subjective response can be seen.

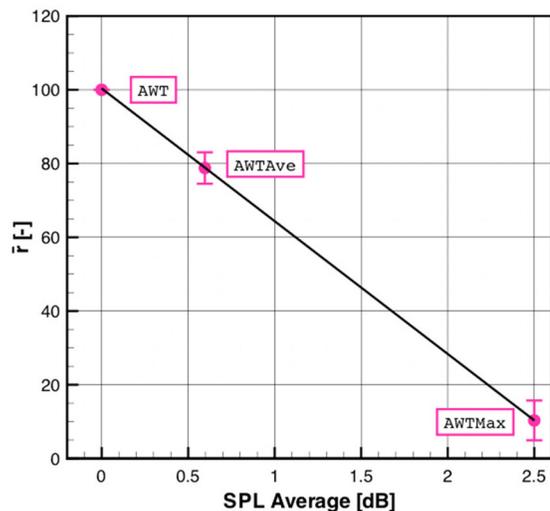


Figure 16. Effect of an increase in SPL

The gradient of this relationship was used to generate a sensitivity coefficient, assessing the degradation in subjective response with an increase in zero-yaw SPL, from:

$$\frac{d\bar{r}}{dL} = -36\text{dB}^{-1}$$

By also determining the gradient of the yaw sensitivity relationship of Figure 15 the comparative sensitivity coefficient assessing the change in subjective response to a change in yaw sensitivity was calculated as:

$$\frac{d\bar{r}}{d\left(\frac{dL}{d\psi}\right)} = -410\psi/\text{dB}$$

These two values provide a comparison of the relative importance of the level of cabin noise measured in a vehicle at zero-yaw with the sensitivity that the cabin noise has towards changes in yaw angle. By determining the quotient of these quantities, this comparison can be expressed quantitatively, defined as the ratio of occupant sensitivity to the vehicle's yaw response compared with their sensitivity to the noise level at zero yaw:

$$\frac{d\left(\frac{dL}{d\psi}\right)}{dL} = \frac{-36\text{ dB}^{-1}}{-410\psi/\text{dB}} = 0.09\psi^{-1}$$

This ratio suggests that a change in yaw sensitivity of a vehicle by 0.09 dB/degree would have the same perceived impact as an increase of 1 dB in the overall level of cabin noise. This does depend on the range of wind conditions to be experienced; these particular values represent a windy day, when a customer might be most aware of wind noise. This highlights the fact that knowledge of the range of wind conditions experienced in the intended market for a particular vehicle may be useful when assessing real-world wind noise performance.

Since both the overall level of cabin noise of a vehicle measured at zero yaw and the sensitivity of the cabin noise to changes in yaw angle can be potentially modified with changes to the vehicle geometry, this comparison provides guidance when assessing these changes during the wind noise development of a vehicle.

## SUMMARY/CONCLUSIONS

A third-octave modulation technique was able to simulate the cabin noise response of a vehicle to the unsteady flow conditions experienced on-road with good fidelity. A quasi-steady response was demonstrated up to approximately 2 Hz with on-road modulation levels about 2 dB below that predicted using the wind tunnel. This amplitude shift was likely to be a result of masking from the additional cabin noise content measured on-road (e.g. road noise) uncorrelated to external aerodynamic unsteadiness.

The use of the simulation approaches described in this paper allows the prediction of the unsteady wind noise of a vehicle to be made through the combination of steady-state cabin noise and on-road flow condition measurements, provided that the aeroacoustic response of the vehicle is dominated by quasi-steady sources. This therefore allows a prediction of how the wind noise of a vehicle may sound when driven in a particular set of wind conditions, which it has not directly experienced. From a vehicle development perspective, this also has the further benefit of allowing non-drivable prototype vehicles or steady-state cabin noise predictions from computational methods to be assessed as they would be in the unsteady on-road environment.

The relative impact of an increase in the level of cabin noise and the sensitivity of the cabin noise to changes in yaw angle was assessed. It was found that a change in yaw sensitivity of a vehicle by 0.09 dB/degree would have the same perceived impact in the cabin as an increase of 1 dB in the overall level of cabin noise at zero yaw. The subjective comparison of these vehicle characteristics can provide guidance when assessing the on-road wind noise performance of different vehicle modifications under steady conditions.

## REFERENCES

- Howell, J., "An Estimation of the Unsteady Aerodynamic Loads on a Road Vehicle in Windy Conditions," SAE Technical Paper [2004-01-1310](#), 2004, doi:[10.4271/2004-01-1310](#).
- Mankowski, O. A. (2013) The Effect of Transient Airflow for Automotive Aerodynamics, PhD Thesis, Durham University.
- Mansor, S., Passmore, M., "Estimation of bluff body transient aerodynamics using an oscillating rig" Journal of Wind Engineering and Industrial Aerodynamics 96:1218-1231, 2008.
- Mayer, J., Schrefl, M., and Demuth, R., "On Various Aspects of the Unsteady Aerodynamic Effects on Cars Under Crosswind Conditions," SAE Technical Paper [2007-01-1548](#), 2007, doi:[10.4271/2007-01-1548](#).
- Ryan, A. and Dominy, R., "The Aerodynamic Forces Induced on a Passenger Vehicle in Response to a Transient Cross-Wind Gust at a Relative Incidence of 30°," SAE Technical Paper [980392](#), 1998, doi:[10.4271/980392](#).
- Wordley, S. J., On-road turbulence. PhD thesis, Monash University, 2009.
- Sims-Williams, D., "Cross Winds and Transients: Reality, Simulation and Effects," *SAE Int. J. Passeng. Cars - Mech. Syst.* 4(1):172-183, 2011, doi:[10.4271/2011-01-0172](#).
- Lindener, N., Miehl, H., Cogotti, A., Cogotti, F. et al., "Aeroacoustic Measurements in Turbulent Flow on the Road and in the Wind Tunnel," SAE Technical Paper [2007-01-1551](#), 2007, doi:[10.4271/2007-01-1551](#).
- Peric, C., Watkins, S., Lindqvist, E., and Saunders, J., "Effects of On-Road Turbulence on Automotive Wind Noise: Comparing Wind-Tunnel and On-Road Tests," SAE Technical Paper [970406](#), 1997, doi:[10.4271/970406](#).
- Oettle, N., Mankowski, O., Sims-Williams, D., Dominy, R. et al., "Evaluation of the Aerodynamic and Aeroacoustic Response of a Vehicle to Transient Flow Conditions," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):389-402, 2013, doi:[10.4271/2013-01-1250](#).
- Oettle, N., Mankowski, O., Sims-Williams, D., Dominy, R. et al., "Assessment of a Vehicle's Transient Aerodynamic Response," SAE Technical Paper [2012-01-0449](#), 2012, doi:[10.4271/2012-01-0449](#).
- Oettle, N., Sims-Williams, D., Dominy, R., Darlington, C. et al., "The Effects of Unsteady On-Road Flow Conditions on Cabin Noise: Spectral and Geometric Dependence," *SAE Int. J. Passeng. Cars - Mech. Syst.* 4(1):120-130, 2011, doi:[10.4271/2011-01-0159](#).
- Oettle, N., Sims-Williams, D., Dominy, R., Darlington, C. et al., "The Effects of Unsteady On-Road Flow Conditions on Cabin Noise," SAE Technical Paper [2010-01-0289](#), 2010, doi:[10.4271/2010-01-0289](#).
- Oettle, N.R. The Effects of Unsteady On-Road Flow Conditions on Cabin Noise, PhD Thesis, Durham University, 2013.
- Irwin, H., Cooper, K., Girard, R., Correction of Distortion Effects Caused by Tubing Systems in Measurements of Fluctuating Pressures, Journal of Industrial Aerodynamics, 1979. 5(1-2), p. 93-107.
- Sims-Williams, D. and Dominy, R., "Experimental Investigation into Unsteadiness and Instability in Passenger Car Aerodynamics," SAE Technical Paper [980391](#), 1998, doi:[10.4271/980391](#).
- Bendat, J. S. and Piersol, A. G. (1993). Engineering applications of correlation and spectral analysis. John Wiley & Sons inc., New York, second edition.
- Schröck, D., Widdecke, N., and Wiedemann, J. Aerodynamic response of a vehicle to turbulent wind. In 7th FKFS conference "progress in vehicle aerodynamics and thermal management", Stuttgart, 2009.
- Watkins, S., "Chapter III: Gusts and Transients in Topics in Wind Noise Automobile Wind Noise and its Measurement Part II," Society of Automotive Engineers, Inc., Warrendale, PA, ISBN 0-7680-0389-X, 1999.

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## DEFINITIONS/ABBREVIATIONS

- ASD** - Autospectral density ( $G_{xx}$ )  
**AWT** - Aeroacoustic Wind Tunnel  
**CSD** - Cross-spectral density ( $G_{xy}$ )  
**H(f)** - Transfer function  
**SPL** - Sound Pressure Level