MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

A method to simulate wind noise in cars under time-varying wind conditions

Carr, Daniel J.[1]
Davies, Patricia[2]
Ray W. Herrick Laboratories
177 S. Russell Street
Purdue University
West Lafayette IN 47907-2031

ABSTRACT

To control wind noise in cars and increase customer satisfaction, better models of wind noise perception are desired. Psychoacoustic tests were conducted to develop a refined acceptance model for stationary wind noise. The goal is now to develop acceptance models for wind noise under unsteady wind conditions, because cars that are acceptable under steady wind conditions may be unacceptable under unsteady wind conditions. To develop an acceptance model for time-varying wind noise, it is first necessary to identify the main characteristics of the non-stationary sounds, and to develop a method of systematically controlling these so that robust listening studies can be designed. A method for simulating unsteady wind noise from stationary wind-tunnel recordings, which is based on an existing approach, has been developed. Stationary wind noise recordings are amplitude modulated based on the speed and direction of the external airflow incident on the vehicle. The effects of the wind variations are used to design a series of FIR filters, and a method for transitioning from one filter to the next during filtering has been developed. Recordings under non-stationary wind conditions are compared to the time-varying modifications to the stationary wind-tunnel recordings to determine the realism and accuracy of the simulations.

Keywords: Noise, Environment, Annoyance
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

It has long been acknowledged that noise inside automobiles resulting from airflow around the vehicle has become more important to control, since effective measures have been found for reducing noise from engines, powertrains, and the contact of tires with pavement.[1] The manner in which this noise is controlled is informed by models of people's perception of the noise, and to more effectively control the noise, better perception models are desired. The authors have conducted two previous listening studies[2,3] to develop improved models of acceptability of stationary wind noise (i.e. noise that can be adequately described using time-averaged statistics). A major conclusion

[1] djcarr@purdue.edu
[2] daviesp@purdue.edu

from these studies is that models based on Loudness and Sharpness metrics predict subjects' responses significantly better than do models based on Loudness alone.

Vehicles deemed acceptable under stationary wind noise conditions are sometimes found not to be acceptable under non-stationary wind conditions. A natural extension of the previous work is to understand and quantify how non-stationary wind noise characteristics affect annoyance. To conduct tests that will enable further development of a wind noise acceptance model, sounds need to be measured or simulated that contain the non-stationary characteristics typically found under driving conditions. Various experimental techniques for producing turbulent flows in wind tunnels have been developed, including rotating the measurement vehicle on a turntable,[4] placing the vehicle in the diffuser or in the shear-layer area,[5] placing a "blocker" object upstream to the vehicle,[5,6,7,8] and installing a special turbulence-generating system.[9,10] An alternative approach is to simulate non-stationary noise directly; this can be done by splicing together stationary noise recordings made at different flow conditions,[11] or by amplitude-modulating a single stationary noise recording,[12] based on a known airflow profile.

Both of these general strategies are attractive in that they produce clean wind noise sounds without any engine or road noise artifacts. The two digital noise simulation methods are valid only under the assumption that the noise is quasi-steady (i.e. the noise depends only on the speed and direction of the airflow, not on the rate at which the airflow changes). However, the advantage of digital simulation methods is that they do not require a separate wind-tunnel testing protocol for non-stationary noise. The only remaining need is for airflow profiles, which are easier to measure.

In this paper, an existing digital simulation approach developed by Oettle, Sims-Williams, and Dominy[12] is examined, and various adjustments and revisions to the approach are proposed. The goal is to have a method where non-stationary wind noise characteristics can be varied in a controlled manner so that their relation to acceptability can be examined.

2. THE ORIGINAL METHOD

This simulation method involves amplitude-modulating a single stationary sound. The validity of the method depends, again, on the behavior of the non-stationary noise being quasi-steady. This is a reasonable assumption if the airflow changes are sufficiently slow.[13] Oettle *et al.* reported quasi-steady behavior of the surface pressure response of the front sideglass up to 2-10 Hz, except in the area close to the A-pillar,[14] and quasi-steady behavior of the interior noise at fluctuation frequencies of up to 2-5 Hz.[15]

A flowchart of the method is shown in Figure 1. Oettle's data contained both airflow profiles and stationary wind noise measurements. Airflow profiles were measured on-road, using a 5-hole probe mounted on the roof of a test vehicle. This placement was to ensure that the quantities reported are the actual wind speed $v(t)$ and yaw angle $\theta(t)$ at the probe location.[12] Stationary wind noise measurements were made in a wind tunnel, using a binaural head, at a range of wind speeds and yaw angles, and the sound pressure level (SPL) was calculated. Continuous surface functions SPL(v,θ) relating sound pressure level to wind speed (v) and yaw (θ) are generated from this data. Surface functions are used to generate amplitude modulation envelopes [$A(t)$] to turn a reference stationary noise recording into a non-stationary wind noise sound. Two versions of this method exist. In the first version, a single modulation envelope is generated for the entire sound. In the second version, the base sound is filtered into 1/3-octave bands, surface functions are generated for each 1/3-octave band, and each band signal is modulated separately, then all the modulated band signals are summed to produce the new sound. This one-third octave band version allows for different flow-related noise changes in different frequency regions.

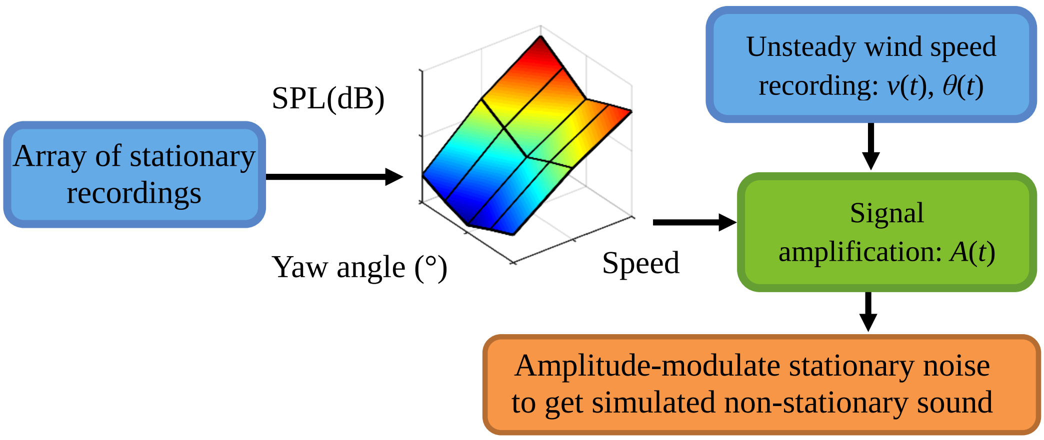

Figure 1. Flowchart of wind noise simulation method.

3. IMPLEMENTATION AND PROPOSED REVISIONS

A custom implementation of this simulation method was written in MATLAB, following the 1/3-octave version of the method. A new set of wind noise sounds was recorded for use in this work, including sounds in three vehicles: a truck, an SUV, and a sedan. Four binaural heads were used for the wind-tunnel recordings.

Two changes were made to the original method in the course of this implementation. The first change was to define the surface functions differently. This was done because the authors' set of stationary noise recordings contained significantly fewer airflow conditions than did Oettle's data. Oettle took measurements at 7 wind speeds (from 108 to 180 km/h) and 17 yaw angles (from –20° to 20° in 2.5° increments), which allowed him to approximate the logarithmic relationship between SPL and wind speed using linear interpolation.[13] On the other hand, the authors' wind tunnel data included 15 measurement points at speeds of 100, 130, and 160 km/h, and at five yaw angles (from –20° to 20° in 10° increments). In order to generate a well-behaved surface from this dataset, a more complex procedure than linear interpolation was needed. An extrapolation method was also needed to define the surface function at higher and lower speeds.

The second change was made to the way in which the modulation envelopes were defined. One-third-octave band-pass filtering and applying modulation envelopes to each band is straightforward, but it may result in some unrealistic spectral effects. Applying the same amplification across an entire 1/3-octave band produces an effective filter frequency response that looks like a staircase, with sharp transitions at the corner frequencies of the bands. These may lead to tonal artifacts in the simulated sound. To avoid this problem, the scaling factors for each 1/3-octave band were used to define a broadband finite-impulse-response (FIR) zero-phase time-varying filter.

3.1 Broadband versus 1/3-Octave Band Implementation

In deciding which version of the simulation method to use, it was necessary to test whether the 1/3-octave method produces significantly more realistic sounds than does the simpler broadband method. This was done by adjusting a wind-tunnel recording to simulate wind-tunnel recordings under different flow conditions. (The SPL values at the given wind conditions are already known, so the scaling factors can be calculated directly without having to interpolate or otherwise define a continuous surface function.) It was found that broadband-adjusted sounds had noticeably different power spectral densities than the target sounds, and were easily distinguishable when listening to them; whereas 1/3-octave adjusted sounds matched the targets more closely. Results from an example case are shown in Figure 2.

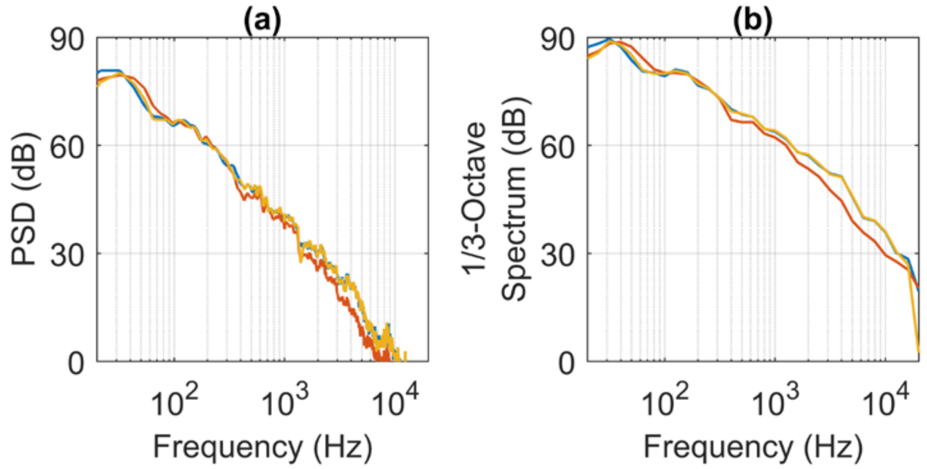

Figure 2: (a) Power spectral densities and (b) 1/3-octave spectra of an SUV sound: original recording at 160 km/h, 20° (blue), single modulation envelope prediction (orange) and 1/3-octave envelope (yellow) predictions from reference signal recorded at 100 km/h, 0°.

3.2 SPL Surface Functions

Hou[16] reports that while variations of SPL with wind speed are generally logarithmic, both for broadband and for 1/3-octave signals, the SPL curve begins to flatten at low speeds for center frequencies of 2 kHz or above. For this reason, and because of the small number of measurement points (15) in the authors' data, more surface shapes than those that are strictly logarithmic as a function of speed were examined.

Surfaces were estimated by using multiple linear regression, and were examined for realism of shape and goodness of fit. These included quadratic, logarithmic, and logistic functions of speed; all surfaces examined were quadratic in yaw. Care was taken to ensure that the function increased monotonically with speed well outside the measurement range, so that extrapolated values would be somewhat realistic. It was also examined whether good surfaces could be obtained when constraining the function to pass exactly through the "reference point" (the SPL value at the flow conditions of the stationary sound being modified). With this constraint, if a steady wind profile with the same flow conditions as the base sound is input to the simulation algorithm, the base sound is returned unmodified.

The most effective procedure found was to extrapolate SPL values so that the speeds ranged from 70 to 190 km/h in the surface functions, and to use these extrapolated values as additional data points when fitting a biquadratic function of yaw and speed. The extrapolated values were generated by fitting logistic functions of speed at each yaw angle; logistic functions were chosen to prevent the surface from flattening out too close to the measurement range. The biquadratic surfaces can usually be constrained to pass through the reference point without sacrificing the requirement of monotonically increasing over the desired speed range. In cases where this requirement is not met, the program is set to re-generate the function without the reference point constraint. An example function is shown in Figure 3 along with the R^2 values for the estimated surface functions in all one-third octave bands.

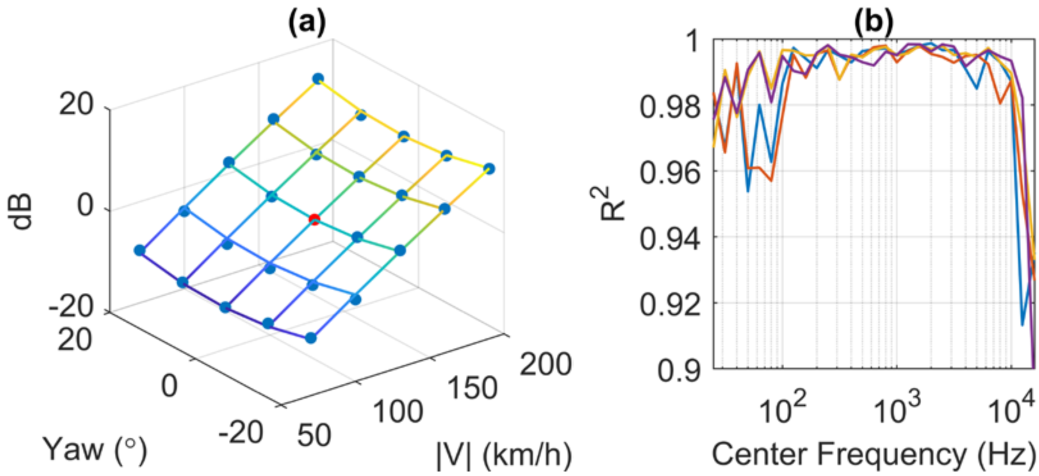

Figure 3: Performance of 1/3-octave amplification surface functions for SUV data, reference point 130 km/h, 0°. (a) Surface function for 1-kHz band, front passenger's left ear (reference point in red); (b) Adjusted R^2 values of all surface functions (colors indicate results for signals from different mannequin ears).

3.3 Time-Varying Filtering

To generate a smooth filter frequency response, the 1/3-octave band scaling factors were connected with a cubic spline curve and resampled to a frequency resolution of approximately 2.7 Hz. Inverse Fourier transforming and Hann windowing the impulse response yielded an 0.07-second-long filter impulse response. This length is sufficient to define frequency components down to 250 Hz; modeling lower frequencies is not believed to be crucial due to high contributions from other noise sources, such as structure-borne road-tire noise[17]. An example of applying this filter-generating method is shown in Figure 4.

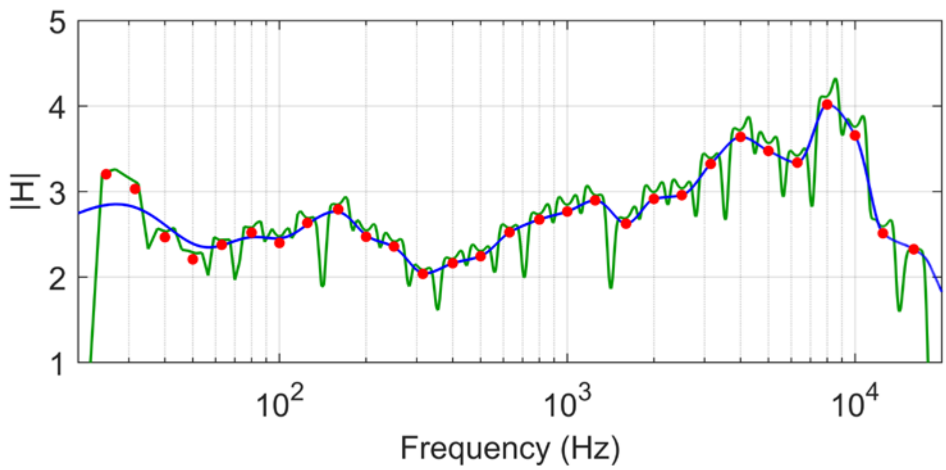

Figure 4: Improvement of simulation spectrum with filter design. Colors indicate: design scaling factors (red); effective frequency response of original envelope procedure (green); frequency response of FIR filter (blue).

A difficulty in using time-varying FIR filters is that implementation can be computationally expensive. If the instantaneous filter coefficients are calculated from the frequency response at each time sample, the program will take more than half an hour to simulate a 15-second sound. One way to reduce run-time is to calculate the exact filter coefficients at longer time intervals (T), and to linearly interpolate the coefficient values at the time samples in between. This process is illustrated in Figure 5. The interpolated values would be expected to be acceptable as long as the time interval (T) is sufficiently short, so that low frequency wind speed variations are nearly linear within this time interval.

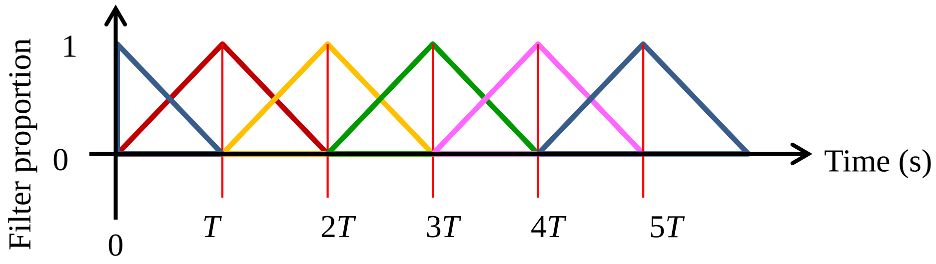

Figure 5: Diagram representing the filter interpolation scheme. Exact coefficients are calculated at every interval T; coefficients at time-samples in between are approximated by taking proportions of the coefficient at the two nearest values of T.

Two tests were conducted to assess the effectiveness of the time-varying filter interpolation scheme. In the first test, an airflow profile with sinusoidal fluctuations was given to the program, and the accuracy of the interpolated filter shapes was examined by calculating the exact filter coefficients at 1/10 the interpolation time interval. It was concluded that if the interpolation time interval is 1/20 the period of the highest frequency component of interest in the wind profile, the frequency response curve of the estimated filter generally deviates from that of the exact filter by 0.1 dB or less.

In the second test, a set of sounds filtered using the interpolation scheme were compared to a set of sounds filtered using exact filters at every time sample. No audible differences between the two types of filtered sounds were observed.

4. VERIFICATION

To test the full simulation method, wind speed and angle profiles based on on-road recordings were used to modify a stationary wind-tunnel recording. The non-stationary recordings were made on a high-speed track at a ground speed of approximately 130 km/h, using the same three vehicles that were used in the wind-tunnel recordings, with two binaural heads on the front and back passenger side of the vehicle.

The airflow profiles were low-pass filtered at 12.5 Hz using a moving-average Hann window. While Oettle *et al.* state 2-5 Hz as the upper frequency limit for the quasi-steady assumption,[15] the frequencies up to 12.5 Hz were included both to allow transient wind events with slow overall periodicity to have fast onsets, and to include a greater proportion of those frequencies believed to contribute most strongly to the perception of fluctuation strength (which Fastl and Zwicker describe as having a maximum at modulation frequencies around 4 Hz[18]).

An example of a wind speed profile and Loudness time histories of a track and simulated sound is shown in Figure 6. (The low-frequency energy of the simulated sound below 250 Hz was replaced with the low-frequency energy of the track sound.) The shapes of the wind speed profile and of the Loudness time histories are clearly similar; and the transient events in the simulations sound reasonably like those in the recordings. Some average sound quality differences are audible between the recordings and the simulations; this is expected to be due to tire tread noise in the track recordings.

It is also noteworthy that when different wind-tunnel recordings were modified to simulate the same track recording, the audible differences between the simulated sounds were subtle at most.

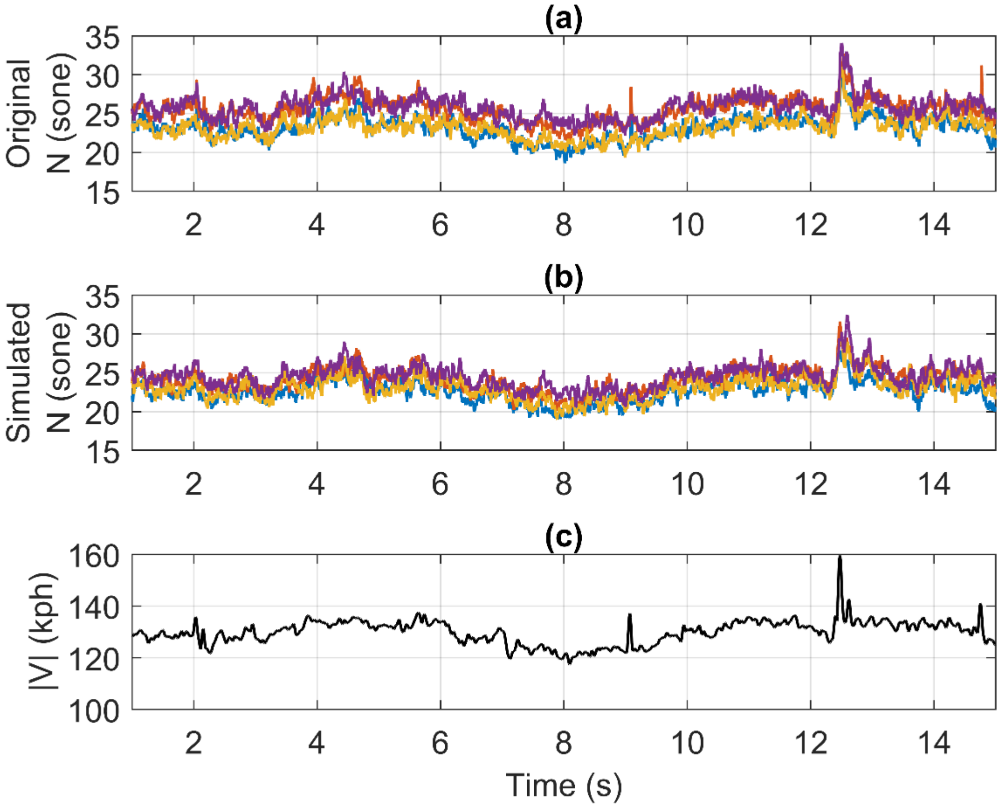

Figure 6: (a) Loudness time history of a track recording in an SUV; (b) Loudness time history of the simulated sound; (c) wind velocity profile derived from the recording and used to generate the simulated sound. Colors in (a) and (b) indicate results for different ears.

5. CONCLUSIONS

A method for simulating non-stationary wind noise in vehicle interiors, proposed by Oettle, Sims-Williams, and Dominy, has been successfully implemented. Revisions to the original method included defining the relationships between SPL and airflow conditions by estimated biquadratic functions rather than linear interpolation, and modulating the base sound by means of time-varying FIR filters rather than envelopes for 1/3-octave bands. This code has been tested for robustness of the algorithm and realism of the simulated sounds, and results are favorable. Future steps in the code's development are expected to include additional refinement of the surface functions, and of the criteria for what frequencies in the airflow profile should be included when running simulations. The code is expected to be used to generate sets of sounds with controlled nonstationary characteristics, for use in listening studies.

5. ACKNOWLEDGEMENTS

The work described in this paper was funded by Ford Motor Company. The authors would particularly like to thank Adam Karlin, William Gulker, Artem Poliakov, and Anil Raju for their advice and consultation.

6. REFERENCES

1. Callister, J. and George, A. Measurement and analysis of automobile wind noise. Proc. of the SAE 1993 International Congress and Exposition, Detroit, MI, USA, March 1993. SAE Technical Paper Series. 1993; 930299.

2. Carr, D. and Davies, P. An investigation into automobile wind noise characteristics beyond loudness that affect people's responses to the sounds heard within the car. In *Proceedings of Inter-Noise 2016*, pages 7364-7372, Hamburg, GERMANY, August 2016.

3. D. Carr and P. Davies. An investigation of the influence of sharpness on people's responses to wind noise inside automobiles. In Proceedings of Noise-Con 2017, pages 749-757, Grand Rapids, Michigan, USA, November 2017.

4. C. Peric, S. Watkins, and E. Lindqvist. Wind turbulence effects on aerodynamic noise with relevance to road vehicle interior noise. *Journal of Wind Engineering and Industrial Aerodynamics*, 69-71:423-435, 1997. Proceedings of the 3rd International Colloquium on Bluff Body Aerodynamics and Applications. Blacksburg, Virginia, USA; July-August 1996.

5. Thompson, M., Watkins, S., and Kim, J., "Wind-Tunnel and On-Road Wind Noise: Comparison and Replication," SAE Technical Paper 2013-01-1255, 2013, https://doi.org/10.4271/2013-01-1255.

6. S. Amman, J. Greenberg, B. Gulker, and S. Abhyankar. Subjective quantification of wind buffeting noise. In *Proceedings of the 1999 SAE Noise and Vibration Conference*, number 1999-01-1821 in SAE Technical Paper Series, Traverse City, Michigan, USA, May 1999.

7. M. Blommer, S. Amman, S. Abhyankar, and B. Dedecker. Sound quality metric development for wind buffeting and gusting noise. In *Proceedings of the SAE 2003 Noise & Vibration Conference and Exhibition*, number 2003-01-1509 in SAE Technical Paper Series, Traverse City, Michigan, USA, May 2003. SAE International.

8. G. Lemaitre, C. Vartanian, C. Lambourg, and P. Boussard. A psychoacoustical study of wind buffeting noise. *Applied Acoustics*, 95:1-12, 2015.

9. N. Lindener, H. Miehling, A. Cogotti, F. Cogotti, and M. Maffei. Aeroacoustic measurements in turbulent flow on the road and in the wind tunnel. *In Proceedings of the SAE 2007 World Congress*, number 2007-01-1551 in SAE Technical Paper, Detroit, Michigan, USA, April 2007. SAE International.

10. S. Terakado, T. Makihara, T. Sugiyama, K. Maeda, K. Tadakuma, K. Tsuboi, M. Iyota, K. Kosaka, and S. Sugiyama. Experimental investigation of aeroacoustic cabin noise in unsteady flow by means of a new turbulence generating device. *SAE International Journal of Passenger Cars - Mechanical Systems*, 10:309-317, March 2017.

11. S. Krampol, M. Riegel, and J. Wiedemann. A procedure to simulate the turbulent noise interior of cars. In *Proceedings of NAG/DAGA 2009*, pages 596-598, Rotterdam, The Netherlands, 2009.

12. Oettle, N., Sims-Williams, D., and Dominy, R., "Assessing the Aeroacoustic Response of a Vehicle to Transient Flow Conditions from the Perspective of a Vehicle Occupant," *SAE Int. J. Passeng. Cars - Mech. Syst*. 7(2):2014, doi:10.4271/2014-01-0591.

13. Oettle, N. “The Effects of Unsteady On-Road Flow Conditions on Cabin Noise”. Ph.D. thesis, Durham University (2013).
14. Oettle, N., Mankowski, O., Sims-Williams, D., Dominy, R., Freeman, C., and Gaylard, A. “Assessment of a Vehicle’s Transient Aerodynamic Response”. Presented at the *SAE 2012 World Congress & Exhibition*, SAE Technical Paper 2012-01-0449, April 2012. SAE International.
15. 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):2013, doi: 10.4271/2013-01-1250.
16. Hou, H., “Automobile Wind Noise Speed Scaling Characteristics,” *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1531.
17. Cerrato, G. Automotive sound quality – powertrain, road and wind noise. Sound & Vibration. 2009; April:6-24.
18. H. Fastl and E. Zwicker. *Psychoacoustics: Facts and Models*, chapter 10. Springer Series in Information Sciences. Springer Verlag Berlin Heidelberg, 3rd edition, 2007.