Section A		
Institution: Durham University		
Unit of Assessment: 12 Engineering		
Title of case study: Assessing Real On-Road Vehicle Aeroacoustics and Aerodynamics		
Period when the underpinning research was undertaken: 2010-2016		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor David Sims-Williams Professor Robert Dominy	Professor Reader	ALL January 1989-February 2015
Period when the claimed impact occurred: August 2013 - December 2020.		
Is this case study continued from a case study submitted in 2014? N		

Section B

1. Summary of the impact

Research at Durham University that enables better assessment of real-world aerodynamic and aeroacoustic performance of road vehicles has been adopted for the development of new vehicles by manufacturers including Jaguar Land Rover (JLR), Nissan and GAC (China). This has resulted in vehicles with better aerodynamic performance, greater energy/fuel efficiency, better aeroacoustic performance (leading to improved driver comfort and less risk of fatigue) and associated positive economic impacts.

The three engineering centres making direct use of Durham's work in this field include the UK's two largest OEMs (Original Equipment Manufacturers) and are together responsible for engineering vehicles with a production of approximately 1.2M vehicles annually. Durham's work in the field is cited by at least six other automotive OEMs.

2. Underpinning research

The aerodynamic and aeroacoustic development of vehicles is typically undertaken using steady-state evaluation environments – both wind tunnels and computational fluid dynamics (CFD) with steady inlet conditions and with a focus on zero-yaw conditions (no crosswind). As a result, there are aspects of the on-road environment that are not captured, including the effects of gusty on-road conditions. These effects may be quasi-steady or fully unsteady and affect the actual and perceived wind noise in the cabin, the handling of the vehicle and energy consumption. The challenge of vehicles in the real world not living up to expectations based on lab measurements and simulations is highlighted in each of [E1], [E2], [E3], [E4].

Work at Durham over two decades has focused on unsteady aspects of vehicle aerodynamics and aeroacoustics including impacts of unsteady on-road conditions. Work has included tests with novel wind tunnel capability at Durham (e.g. [R4], [R5]) and in external facilities (e.g. [R1], [R2], [R3]), on-road measurements using instrumentation developed at Durham (e.g. [R1], [R2], [R3]) and CFD. The work has also included psychoacoustic evaluations to assess the importance of wind noise modulation on perceived noise levels (e.g. [R3]).

The work with the clearest impact to date has involved simultaneous on-road measurements of onset flow, surface pressures and cabin noise making use of Durham's instrumentation and data analysis techniques (e.g. [R1], [R2], [R3]). This has shown how the performance of a vehicle in this environment can be predicted based on wind tunnel measurements in a steady environment (e.g. as in Figure 1). The research showed that surveying the on-road environment with an instrumented vehicle is important and provided a methodology for doing this. Earlier work on the topic had often assumed that that the on-road environment could be assessed by stationary observations using Taylor's hypothesis, but that approach fails to recognise the dominant significance, the spatial distribution of the on-road natural wind, experienced by the moving vehicle as a temporal variation. Of particular significance is that the work successfully demonstrated the full path to predict accurately the real-world performance. Further, combining on-road measurements of onset flow, wind tunnel measurements of vehicle response and psychoacoustic evaluations has shown that the modulation of cabin noise by time-varying onset conditions is an important factor (eg: [R3]).

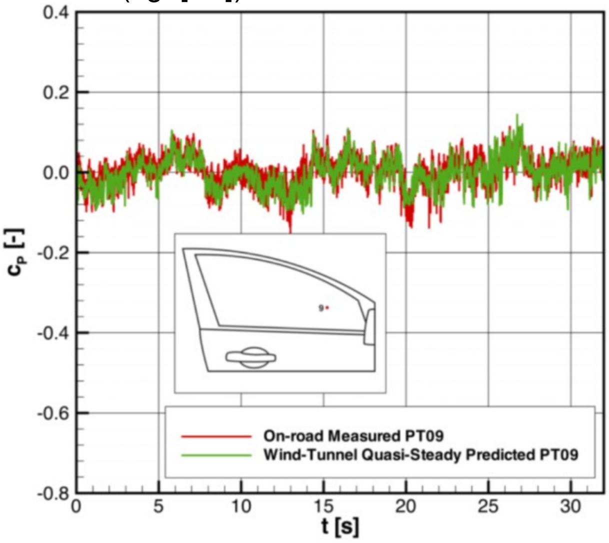

Figure 1 – Comparison between on-road measurement and prediction using a wind tunnel measurement with Durham's on-road instrumentation and analysis method – from [R2]

3. References to the research

[R1] Oettle, N, Sims-Williams, D, Dominy, R, Darlington, C, Freeman, C, The Effects of Unsteady on-Road Flow Conditions on Cabin Noise: Spectral and Geometric Dependence, SAE Paper 2011-01-0159, SAE International Journal of Passenger Cars - Mechanical Systems, 2011. doi:0.4271/2011-01-0159

[R2] 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 Paper 2013-01-1250 SAE International Journal of Passenger Cars - Mechanical Systems 6(1):389-402, 2013, doi:10.4271/2013-01-1250.

[R3] 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 International Journal of Passenger Cars - Mechanical Systems 7(2):550-558, 2014, doi:10.4271/2014-01-0591.

[R4] Mankowski, O., Sims-Williams, D., and Dominy, R., A Wind Tunnel Simulation Facility for On-Road Transients, SAE International Journal of Passenger Cars - Mechanical Systems 7(3):1087-1095, 2014, doi:10.4271/2014-01-0587.

[R5] Kremheller, A., Moore, M., Le Good, G., Sims-Williams, D., Newbon, J., Lewis, R., The Effects of Transient Flow Conditions on the Aerodynamics of a LCV Concept using CFD and Wind Tunnel Experiments, International Vehicle Aerodynamics Conference, Coventry, 2016. https://dro.dur.ac.uk/22383/1/22383.pdf

This research is published in internationally respected peer-reviewed journals and conferences. [R1] was submitted to REF2014 and was graded between 2* and 4* (as all outputs submitted from the UOA were within this range, with the greatest proportion being graded 3*).

4. Details of the impact

Research at Durham has developed measurement and analysis methodologies that are able to better assess the aerodynamic and aeroacoustic performance of road vehicles in real-world conditions.

Impacts:

1-These methodologies have been adopted by multiple automotive original equipment manufacturers (OEMs) in their processes for the development of new vehicles ([E1], [E2], [E3], [E4], [E5], [E6]).

2-This in turn leads to vehicles that have better aerodynamic performance (more fuel efficient under real-world conditions, [E2], [E4], [E6], [E8]) and better aeroacoustic performance (more appealing to customers [E1], [E2], [E5], [E6]), bringing economic benefits. There are also indications of improved safety [E4] including reduced driver fatigue [E5].

Background:

The automotive industry is a major contributor to the UK economy, with an annual turnover exceeding GBP78B and employing approximately 850,000 people (Society of Motor Manufacturers and Traders Industry Facts 2020). The two largest producers in the UK are Jaguar Land Rover (JLR) and Nissan, each producing approximately 350,000-500,000 vehicles per year in the UK.

The reduction of vehicle cabin noise is desirable to customers and hence for manufacturers [E1], [E2], [E5], [E6] and highlighted by the JD Power customer satisfaction rankings, where wind noise is consistently one of the top 3 complaints across all vehicles (e.g.: 2017 U.S. Initial Quality Study Key Stats).

Transport is the largest energy consumer and producer of greenhouse gas emissions in the UK (UK Energy in Brief 2019, BEIS). Aerodynamic drag is a principal energy consumer for road vehicles, affecting fuel consumption, emissions and electric vehicle range [E6], [E8].

As a result of not handling the implications of unsteady on-road conditions it has, in the past, been possible to develop vehicles that perform well according to their development metrics/targets, but which do not meet expectations in practice [E1], [E2], [E3], [E4], [E5], [E6], [E7], [E8]. Durham's research is used by industry to set smarter development metrics/targets, accounting for the on-road environment, resulting in vehicles with better real-world performance in terms of cabin noise and vehicle energy consumption.

Impact via Jaguar Land Rover (JLR):

Prior to working with Durham, JLR had experienced an issue with a vehicle meeting its wind noise targets but experiencing gust modulation in windy conditions on-road. A collaborative research project was undertaken with Durham to better understand wind effects and how to quantify them (outputs including [R1], [R2], [R3]). This resulted in a methodology that is now used within the company and the adoption of a new metric by the company for assessing real-world aeroacoustic performance [E5]. New production parts were introduced to improve this aspect of the performance of the vehicle and sales of this model have subsequently grown ahead of its competitors to approximately GBP1B per annum [E5]. JLR recruited the PhD student involved in the work at Durham "*in part to work towards integrating the results from his (sic) published work into the vehicle development process*." [E1].

From Technical Lead for Wind Noise, Jaguar Land Rover [E1]:

"The techniques developed…at Durham have been integrated in a number of direct and indirect ways into the development process…the Durham-based research has allowed for a more robust virtual sign off, reducing the number and severity of issues in the field."

"Since the collaboration with Durham University began over a decade ago, wind noise issues have significantly reduced on Jaguar Land Rover vehicles, from being considered a systemic issue to that which results in a refined customer experience."

Impact via Nissan:
Nissan Technical Centre Europe (NTCE), seeing [R1] and [R2] and recognising the relevance, initiated a programme to develop their methodology and approached Durham for assistance. They adopted instrumentation and methodologies from [R1] and [R2] for their ongoing work in the development of new vehicles, in particular for setting vehicle performance targets which ultimately determine the performance of the production vehicle.

A senior Nissan engineer comments [E2]:
"It had been an ongoing difficulty for us to compare aeroacoustic results measured on-road with each other and with wind tunnel measurements, due to the inconsistent airspeed and yaw angle in real world conditions."

"We adopted instrumentation developed by Durham and have implemented their data analysis methodology in our own software. As a result, we were able to achieve a step-change improvement in our ability to evaluate results on-road."

"*Durham's instrumentation and methodology now plays a key role in determining the aeroacoustic performance of the vehicles that we develop. This approach has been adopted for all Nissan vehicle programmes which are engineered and manufactured in Europe. This represents about 500,000 vehicles per year, exported to over 100 different countries. The largest share of these are manufactured at Nissan Motors UK."*

Impact via GAC & CAERI:
The China Automotive Engineering Research Institute (CAERI) provide automotive test facilities for OEMs, including test track facilities and greater thanUSD100M wind tunnel facility and have implemented methodologies developed at Durham for use by OEMs in China [E3], [E7].

GAC Group is a Chinese OEM who develop (engineer) their own vehicles (annual production 380,000 vehicles) [E4]. They had observed discrepancies in on-road performance, in particular with regard to electric vehicle range [E4] and they recognised the relevance of [R1] and [R3]. They have subsequently been using the methodologies introduced by Durham and working with CAERI to survey roads across China and have adopted a new metric for the assessment of aerodynamic drag accounting for on-road wind effects. As for other OEMs, Durham's work is being used to set smarter vehicle performance targets, resulting in better real-world vehicle performance [E9].

From CAERI [E3]:
"Based on the published papers, such as SAE 2011-01-0159 and SAE 2014-01-0591, CAERI integrated the test system for road test, and has completed the road test….In the process, some OEMs joined the study and became our collaborators, such as GAC."

From GAC [E4]:
"Since the beginning of our electric vehicle programs in 2016, we noticed discrepancies between the range we predicted from simulation models and the on-road tests."

"We came across papers published by the team lead by Professor Sims-Williams…The work gave us inspirations for hardware instrumentation as well as data analysis methodology. We successfully instrumented the test vehicle and collected valuable on-road test data in 2020."

"Based on the results, we updated our aerodynamic drag criteria…The updated aerodynamic criteria apply to all vehicle development programs, impacting the fuel economy and safety of all of the vehicles we produce and sell every year."

Further Impacts:
Beyond the impacts outlined above, Durham's papers in the field have also been referenced by Engineers at Volvo, Toyota, Tesla, Souest (Fujian), BMW, Hyundai and Kia indicating that this work is also making some contribution to the development of methodologies employed in those OEMs. A list of the relevant references is provided in [E9].

5. Sources to corroborate the impact

[E1] Statement from Technical Group Leader, Aeroacoustics, Jaguar Land Rover on their use of methodologies developed at Durham.

[E2] Statement from Senior Engineer for Aerodynamics and Aeroacoustics, Nissan Technical Centre, Europe on their use of instrumentation and methodologies developed at Durham.

[E3] Statement from Research and Development Director, CAERI Wind Tunnel Center on their use of methodologies developed at Durham.

[E4] Statement from Principal Engineer, GAC Group Research and Development – Aerothermal Performance Section on their use of methodologies developed at Durham.

[E5] Technical Group Leader, Aeroacoustics, Jaguar Land Rover.
(This individual can corroborate the importance of Wind Noise to customer satisfaction, that Durham undertook work with prototype components that ultimately led to improved noise performance on a production vehicle and that JLR has adopted methodologies developed initially at Durham).

[E6] Senior Engineer for Aerodynamics and Aeroacoustics, Nissan Technical Centre, Europe.
(This individual can corroborate the importance of the on-road wind environment to aeroacoustics, fuel consumption and electric vehicle range and Nissan's use of instrumentation and methodologies from Durham.)

[E7] Research and Development Director, CAERI Wind Tunnel Centre.
(This individual can corroborate CAERI's implementation of instrumentation and methodologies based on work at Durham and their use to survey roads across China.)

[E8] Principal Engineer, GAC Group Research and Development – Aerothermal Performance Section.
(This individual can corroborate the use of methodologies based on work at Durham to survey roads across China and the adoption by GAC automotive of new vehicle drag criteria based on an understanding of the on-road environment derived from Durham's work in order to make more realistic assessments of vehicle energy consumption and electric vehicle range.)

[E9] Dossier of additional automotive OEMs who reference Durham's research connected with this impact case study; to confirm its broader impact across the automotive industry (BMW, Hyundai, Kia, Souest Fujian, Tesla, Toyota, Volvo).