Institution: Coventry University		
Unit of Assessment: 12		
Title of case study: New exhaust system design for reducing transport emissions		
Period when the underpinning research was undertaken: 2000-2020		
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:**
E. Abo-Serie	Assistant Professor	2007-2010, 2016 - present
S. Aleksandrova	Assistant Professor	2006 - present
C. Bastien	Associate Professor	2007 - present
S. Benjamin	Emeritus Professor	1989 - present (Emeritus from 2015)
J. Christensen	Assistant Professor	2010- present
H. Medina	Assistant Professor	2009- present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

An efficient design process for exhaust systems is key in delivering reductions in emissions of toxic gases and particulates from road vehicles. Coventry University's research has enabled the development of new lightweight exhaust systems and a state-of-the-art after treatment utilised by UniPart and Jaguar Land Rover (JLR).

For UniPart and JLR, this has already resulted in substantial fuel savings across the vehicle fleet, a considerable time reduction in prototyping and the design processes, and more accurate predictions of the exhaust pressure distribution.

2. Underpinning research (indicative maximum 500 words)

The underpinning research focused on the development of physics-based, experimentally validated, computationally-efficient tools for modelling and optimisation of exhaust systems, to help designers to reduce pressure losses, weight, and cost, whilst not compromising safety or air quality. Several novel modelling techniques have been developed, such as an advanced porous medium approach model and oblique entrance correction model used for modelling catalytic converters [R1,R2,R3], new models for particulate filters [R4] and a numerical framework for ‘holistic’ optimisation of exhaust systems taking into account manufacturing constraints [R5, R6]. These have been supported by experimental studies, enabling better understanding of flow physics, and providing model validation data [R1, R3, R4].

In the porous medium approach, the catalyst honeycomb is represented by a porous region with equivalent resistance properties, thus reducing computational costs. Professor Benjamin's group pioneered the inclusion of ‘oblique entrance correction’, which accounts for the extra flow losses caused by the flow entering the device channels at an angle [R03], particularly important for turbocharged engines with highly swirling flows. The group has advanced the porous medium approach concept to enable modelling three-dimensional problems with heat transfer and chemical introduction of gasoline particulate filters led to a collaboration with JLR, led by Dr Aleksandrova and culminated in the development of new filter testing techniques and 0- and 1-dimensional models. The presence of turbulence in filter channels has been demonstrated experimentally for the first time and was therefore included into the new filter model [R4].

On the system level, exhaust system optimisation has not only involved improvement in emissions and heat transfer, but also noise and vibration levels and mechanical stress, all of this within manufacturing, spacing and costing constraints. These were the focus of the VexPro project [G3] led by Dr Bastien. This research linked the manufacturing process, the effects of structural damage from manufacturing, welding and corrosion, structural stiffness and any forced responses of the exhaust system to the exhaust mass. It resulted in the development of a comprehensive, computationally-efficient optimisation framework for designing lightweight, low cost exhaust systems with improved durability and improved structural and acoustic properties [R5].

The Innex project [G2] led by Dr Bastien, combined our expertise in the modelling of emissions aftertreatment devices and the whole reactions and developed a new model of Selective Catalytic Reduction for steady and transient flows [R1] [G1]. Dr Aleksandrova and Dr Medina developed a method of using a thin porous block to replace a part of the catalyst (hybrid approach), thus combining improved accuracy with reduced computational cost [R2].
The recent exhaust system, providing a base for multi-physics optimisation. The framework developed during VexPro has been enhanced to include the design of the hot-end of the exhaust system (i.e. the part including the catalyst), by accounting for the resulting reduced stiffness effects due to the material being under high heat (typically around 800˚C) and the effect of the catalyst on the system pressure drop. This framework has been successfully implemented in several case studies, including the optimisation and lightweighting of the exhaust hot-end emissions [R6] completed in collaboration with UniPart and JLR.

3. References to the research (indicative maximum of six references)

[R1] Benjamin, S. F., Gall, M. and Roberts, C. A. (2012) 'Tuning the Standard SCR Reaction Kinetics to Model NO Conversion in a Diesel Engine Exhaust SCR Catalyst System Under Steady State Conditions in 1D and 3D Geometries Using Ammonia Gas as the Reductant'. SAE Technical Paper 2012-01-1636 https://doi.org/10.4271/2012-01-1636

[R2] Porter, S., Saul, J., Aleksandrova, S., Medina, H. and Benjamin, S. (2016) 'Hybrid flow modelling approach applied to automotive catalysts'. Applied Mathematical Modelling 40 (19-20):8435-8445 https://doi.org/10.1016/j.apm.2016.04.024

[R3] Quadri, S.S., Benjamin, S.F., & Roberts, C.A. (2009) 'An experimental investigation of oblique entry pressure losses in automotive catalytic converters'. Proceedings of the Institution of Mechanical Engineers, Part C:Journal of Mechanical Engineering Science 223(11):2561–2569 https://doi.org/10.1243/09544062JMES1565

[R4] Aleksandrova, S., Saul, J., Prantoni, M., Medina, H., Garcia Afonso, O., Bevan, M. and Benjamin, S. (2019) 'Turbulent flow pressure losses in gasoline particulate filters'. *SAE Int. J. Engine*s 12(4):455-470 https://doi.org/10.4271/03-12-04-0030

[R5] Hussin, A., Bastien, C., Jones, S., Christensen, J., Medina, H. & Kassem, H. (2017) 'Investigation of baffle configuration effect on the performance of exhaust mufflers'. Case Studies in Thermal Engineering 10:86-94 https://doi.org/10.1016/j.csite.2017.03.006

[R6] Cirstea, R., Abo-Serie, E., Bastien, C., and Guo, H. (2018) 'Modelling of a Coupled Catalyst and Particulate Filter for Gasoline Direct Injection Engines'. SAE Technical Paper 2018-01-0986 https://doi.org/10.4271/2018-01-0986

Grants

[G1] EPSRC 2008-11 (EP/F036175/1) Modelling NOx reduction by selective catalytic reduction (SCR) appropriate for light-duty vehicles under steady state and transient conditions £324K + in kind. PI: Prof S. Benjamin

[G2] Innex (July 2015-June 2017). The total award was £973, 823, of which Coventry University was allocated £229,027 by Innovate UK. PI: Dr C. Bastien

[G3] Vexpro (January 2014-November 2016). Coventry University was awarded £323,881, by Innovate UK. Project partners included Jaguar Car Ltd, EMCON Technologies Germany Aug GmbH and Johnson Matthey PLC . PI: Dr C. Bastien

4. Details of the impact (indicative maximum 750 words)

Coventry University (CU) exhaust system research has been carried out in close collaboration with the automotive industry (JLR, Fiat, Aston Martin) and suppliers (UniPart, Johnson Matthey). A range of new modelling tools have been adopted and used to reduce, not only development times, but vehicle carbon and toxic emissions. Use of these has transformed product development practices resulting in a broad range of economic and environmental impacts.

Economic Impact

1. The multi-physics modelling insights and tools developed as a result of the VexPro and Innex projects, were used by UniPart in their work with Aston Martin, JLR and Fiat, leading to important changes that accelerated and improved design processes [S1]:

    - The new optimisation framework enabled UniPart to realize “A major reduction of development time from 16 to two weeks through the creation of automated tools for rapid development of optimal exhaust systems”, representing a step change for UniPart’s strategic planning of manufacturing processes. It has contributed to their in-house good practice guidelines and continues to inform new exhaust system designs [S1]
    - Cold and hot end exhaust optimisation facilitated a “29% mass reduction (or 2.85kg) from the original 9.83kg exhaust system for a Fiat Brazil mass-produced application (600,000 vehicles per annum)”, significantly reducing material costs.
    - Improved muffler design at Aston Martin resulted in a 47% reduction in the cold end exhaust system mass. This “new design was implemented on all Aston Martin Zagato models from 2016 onwards”. Halving the exhaust system mass, resulted in significant cost reduction for manufacturers and end users.

2. The catalyst modelling tools, in particular the advanced porous medium approach with oblique entrance effect, “have played a vital role in advancing JLR's capability in the area of aftertreatment system modelling”, and are now incorporated into JLR design procedures, thus enhancing the design of the new aftertreatment systems [S2]. The improved urea spray models developed by CU, within the EPSRC project, have led to the introduction of new NOx reducing technologies. “Since 2014, the tools incorporating the improved urea spray models have been used in development of 30 diesel exhaust systems.” [S2] Without this new capability, these automotive manufacturers would have been unable to achieve the compliance with stringent emissions regulations, EU5 (introduced in January 2020) and SULEV (super ultra low emissions vehicle), necessary to participate in the market.

    - New Particulate Filter models developed by CU have been implemented in JLR design process for all coated Gasoline Particulate Filter substrates from 2018 and have been extended for use on Diesel Particulate filters in 2019. This resulted in [S2] “

considerable improvements in the model accuracy over a wide operating range driven by the Real World Driving (RDE) requirements, thus enabling us to make early robust decisions on aftertreatment optimisation without waiting for physical testing, typically bringing forward the decision points by a build phase (12 months)".

3. Inclusion of the new, physics-based and experimentally validated modelling tools in standard JLR design procedures, leading to a change of practice at JLR, in the development of new aftertreatment systems. [S2]

Environmental impact

The role of the exhaust system is to reduce toxic car emissions and ensure safe disposal of hot exhaust gases. However, there is a trade-off between safety, toxic emissions reduction, fuel consumption (carbon emissions) and costs. Our research on the improved prediction of exhaust pressure losses, heat transfer and chemical reactions, combined with new optimisation tools, has been instrumental in supporting UniPart's "strategic aims to reduce [the] car environmental footprint" [S01] and JLR's "ambitions of providing cleaner [and] more efficient vehicles" [S2].

- Reduction of the exhaust system mass has not only lowered manufacturing costs and use of materials (carbon footprint) for Unipart but has also had a major effect on fuel consumption during a car's lifetime. The 47% reduction in the exhaust mass has resulted in [S1] "saving an estimated 50,000 litres of fuel across the fleet (9.7kg mass reduction saves 85 litres of fuel per vehicle over its life, or 0.03395 litres per 100km) and 128 tonnes of CO_2 saved, based on a calculation of 9gCO_2 saving per kilometre"

Improved understanding of the effect of swirl on modelling accuracy at JLR, facilitated by the refinement of the porous modelling approach and the oblique entrance correction, resulted in "improved substrate pressure loss predictions by around 20% on average. It has been adopted in our standard modelling practice for all catalyst substrates and has been used on all of our turbocharged models since 2015." This is crucial for engine downsizing - the major trend aimed to reduce global transport carbon emissions. "This has been critical for improved emission performance with catalysts fitted close to the engine turbo charger for reduced heat loss". JLR's adoption of the urea spray models in the development of 30 diesel exhaust systems since 2014, ensuring compliance with EU5 / SULEV emissions regulations, has reduced vehicle toxic emissions [S2].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Testimonial letter of support from Technology Director, Unipart Manufacturing Group, Beresford Avenue, Coventry, CV6 5LZ

[S2] Testimonial letter of support from Manager Concept Simulation and Methods, JLR Whitley, Abbey Road, Whitley, Coventry, CV3 4LF