Institution: Loughborough University		
Unit of Assessment: B12 Engineering		
Title of case study: Improvements in fuel economy, emissions and reliability for engines and powertrains on high performance vehicles.		
Period when the underpinning research was undertaken: 2005 – 2019		
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:**
Homer Rahnejat	Professor of Dynamics	2000 – 2019
Paul King	Senior Lecturer	1989 – present
Stephanos Theodossiades	Professor of Non-Linear Dynamics	2002 – present
Steve Rothberg	Professor of Vibration Engineering	1995 – present
Ramin Rahmani	Senior Lecturer in Dynamic Tribology	2009 – present
Mahdi Mohammadpour	Senior Lecturer in Dynamics	2018 – present
Nick Morris	Senior Lecturer in Dynamics Energy and Propulsion Systems	2014 – present
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? N		

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

The UK's automotive industry is a key strategic sector; it represents £19bn to the UK economy annually and employs 160,000 people including 38,000 in motorsport. Loughborough research on reducing frictional and dynamic mechanical losses has delivered step-change insights into engine and powertrain behaviour for internationally recognised, sector-leading on- and off-highway vehicle manufacturers and Formula One race teams. Specifically, building models from the interactions between lubricant and micro-deformed surfaces up to whole engines and gearboxes has 1) reduced CO_2 emissions through improved fuel economy for Aston Martin and JCB, and 2) achieved 100% gearbox reliability for Mercedes Grand Prix, the world's leading Formula 1 race team, delivering championship-winning performances every year since 2017.

2. Underpinning research (indicative maximum 500 words)

For two decades, the Dynamics Research Group at Loughborough has been pioneering developments in integrated multi-physics, multi-body dynamics and tribological modelling of engineering systems across different size scales. Since 2005, a team led by Prof Homer Rahnejat has extended this research and applied it to reducing frictional and dynamic mechanical losses in vehicle powertrains, responding to industrial demand for lightweight, downsized systems to improve fuel consumption alongside stringent emission regulations.

The approach pursued was predictive modelling of engineering systems by establishing the inexorable links between component dynamic deformations and tribology **[R1],** essentially introducing the term "tribodynamics" in the scientific literature, supported by extensive validation in the laboratory and in-situ **[R2]**. The system modelling approach considers interacting physical phenomena within a common framework and across scales: large rigid body motions (e.g. crankshaft rotation and piston primary translation) are combined with smaller vibratory motions of components, (e.g. piston skirt thermal and elastic distortion and compression ring deflection of 10-100 μm), together with lubricant film thickness (in μm). For example, in an engine, the crankshaft kinematics drive the piston model, which interacts with the compression ring model, which interacts with the cylinder liner model via the lubricant between them which has behaviour influenced by heat generation. This system approach is generic and can be applied equally well to many subsystems (e.g. engine, clutch, gearbox, differential and their associated components) and then built up to model a complete powertrain. Increased computational power and advanced numerical techniques have made this multi-scale, multi-physics modelling practically possible.

Transient numerical models were developed to study how piston compression ring dynamic deformation and its sealing function contribute to engine frictional losses, building up to studying the effect of cylinder de-activation on friction losses at the compression ring **[R3]** (combining transient lubrication, lubricant rheological state, friction due to lubricant viscous action and surface asperity interactions). The numerical predictions were extensively validated from high performance single cylinder test engines to fully functional (Aston Martin) engines, ultimately modelling cylinder de-activation for the new Aston Martin V12 engine concept.

Our team's work on wheeled off-highway vehicle powertrains required a system-level study of lubricated surfaces in concert with component surface geometry and topography, lubricant properties and load bearing capacity. The above parameters were optimised by studying the coupled dynamics and efficiency of critical powertrain subsystems, such as wheel-hub planetary gear sets (multi-objective optimisation studies involving planetary gear mesh phasing, tooth profile modification and durability) **[R4]**, wet multi-plate brake packs **[R5]** and wet clutch systems (considering thermal and cavitation effects). The links between the various subsystems (to reach system-level modelling) were established by implementing boundary conditions (loading, kinematics etc.) obtained by experimental testing and measurements taken in complete powertrains.

The tribodynamics of manual transmissions and differentials have been systematically investigated for several applications (passenger cars, high performance transmissions, off-highway vehicles) and gear geometries (spur, helical, hypoid, bevel). Research specifically on high performance vehicle transmissions predicted the dynamics and friction loss of meshing gears with teeth profile micro-geometry modifications **[R6]** and explored how lubricant additives affect friction and wear when gear teeth make contact. This delivered reliability improvements under the conditions of extreme high torque and high speed encountered in F1 racing.

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

R1 Littlefair, B., De la Cruz, M., Theodossiades, S., Mills, R., Howell-Smith, S., Rahnejat, H., Dwyer-Joyce, R. S. (2014). Transient tribo-dynamics of thermo-elastic compliant high-performance piston skirts. *Tribology Letters*, 53, pp. 51–70. DOI: https://doi.org/10.1007/s11249-013-0243-6.

R2 Gore, M., Theaker, M., Howell-Smith, S. J., Rahnejat, Homer; King, P. D. (2014). Direct measurement of piston friction of internal-combustion engines using the floating-liner principle. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 228 (3), pp. 344-54. DOI: https://doi.org/10.1177/0954407013511795

R3 Bewsher, S. R., Turnbull, R., Mohammadpour, M., Rahmani, R., Rahnejat, H., Offner, G. and Knaus, O. (2016). Effect of cylinder de-activation on the tribological performance of compression ring conjunction. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 231 (8), pp. 997-1006. DOI: https://doi.org/10.1177/1350650116684985.

R4 Fatourehchi, E., Mohammadpour, M., King, P. D., Rahnejat, H., Trimmer, G. (2017). Effect of mesh phasing on the transmission efficiency and dynamic performance of wheel hub planetary gear sets. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 232 (19), pp. 3469-81. DOI: https://doi.org/10.1177/0954406217737327

R5 Leighton, M., Morris, N., Trimmer, G., King, P. D., Rahnejat, H. (2018). Efficiency of disengaged wet brake packs. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 233 (6), pp. 1562-69. DOI: https://doi.org/10.1177/0954407018758567

R6 Elisaus, V., Mohammadpour, M., Theodossiades, S., Rahnejat, H. (2017). Effect of teeth micro-geometrical form modification on contact kinematics and efficiency of high performance transmissions. *Proceedings of the Institution of Mechanical Engineers, Part*

K: Journal of Multi-body Dynamics, 231 (3), pp. 538-55. DOI: https://doi.org/10.1177/1464419317710157

The underpinning research was published in international, peer-reviewed journals. It was undertaken with the support of a peer-reviewed, competitively awarded EPSRC programme grant (Encyclopaedic: £2.55M total, £1.17M to LU, 2009-2014), whose many project collaborators included Aston Martin, and an Innovate UK project (ECO Driveline, £500k, 2015-17) in collaboration with JCB.

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

The impacts claimed in this case study provide solutions to major practical challenges of performance and reliability for heavy duty engines and powertrains, based on two decades of fundamental research on the integration of multi-physics, multi-scale, multi-body dynamic and tribological modelling at Loughborough University **[R1, R2]**. These impacts are the result of a series of collaboratively funded projects in which the close partnerships with three global motor industry brands were the critical pathways to impact:

1. Aston Martin - the iconic world-leading British manufacturer of high-performance prestige cars with 2500 employees,
2. JCB – the instantly-recognisable manufacturer of off-road construction and agricultural vehicles with 12000 employees and factories in 5 continents, and
3. Mercedes Grand Prix - the top Formula 1 race team of the last decade, winning the Constructors' World Championship for a record seventh consecutive year in 2020, including Lewis Hamilton's 4 successive championships since 2017

The three companies also exemplify the different ways in which such partnerships are initiated. One is a longstanding partnership stretching back several decades with links to teaching and research (JCB), one was initiated by an invitation to support a major grant proposal (Aston Martin), based on the networking activity of the lead academic, and the third (Mercedes Grand Prix) was also through the networking efforts of the lead academic coupled with the growing reputation of the Loughborough team's work in the automotive industry. The relevance of the Loughborough research and the links with industry were also inspired and enabled by the Visiting Professor appointment of Richard Parry-Jones CBE, former Group Vice-President at Ford Motor Company, who became Co-Chair of the UK Automotive Council in 2009.

Impact 1: Reduced CO_2 emissions through improved fuel economy for leading UK vehicle manufacturers

Our research on engine modelling enabled prestige passenger vehicle manufacturer Aston Martin to achieve mandated CO_2 emissions in its new flagship V12 engine **[R3]**. The critical contribution was the engine modelling capability developed at Loughborough and used by Aston Martin to prove a radical engine concept **[S1]** for cylinder deactivation.

The V12 engine is the power unit for the Aston Martin DB11, described as "*the most important Aston in the company's 103-year history*" (CEO Andy Palmer in a 2016 Autocar review), with almost 4000 European sales since launch.

CO_2 emissions for the DB11 had to be reduced to 265g/km, compared to 325g/km for its predecessor (DB9), to meet the company's glidepath for CO_2 reduction as agreed with the EU Commission (and subsequently with California Air Resource Board and the US Environmental Protection Agency). Aston Martin had to meet this challenge and our research made that possible. Failure to achieve the target would have resulted in fines and significant reputational damage. The Chief Engineer at Aston Martin [2001-17] reported that:

"Aston Martin were developing a new V12 turbocharged engine with very challenging fuel economy and CO_2 emissions targets. The key to achieving the targets was cylinder deactivation WITHOUT complicated valve mechanisms and their associated losses and durability challenges, enabling 6 cylinder running in normal driving conditions. The Loughborough modelling was the only way to confirm the viability of the Aston Martin concept. It triggered a multi-million pound development investment but we also estimated a saving of £4M on the development programme we would otherwise have needed. The system was a great success, with an additional benefit in reduced parts cost on every engine. The DB11 went into production with the new V12 engine with unprecedented real world fuel economy figures of up to 30mpg and emissions below 265g/km, as required, resulting in almost 4000 European sales since launch. Based on cylinder deactivation being worth up to 5 grammes of CO_2/km and EU sales of 1000 cars per annum, a fine of almost €0.5M per annum could have been incurred, as well as big reputational damage". **[S2]**

Further, our validated powertrain modelling research **[R4, R5]** with off-road heavy-duty vehicle manufacturer JCB was incorporated into the design of the new JCB 'Eco-Axle Driveline', which significantly reduced CO_2 emissions through improved fuel economy on the JCB 'Backhoe Loader', 'Wheeled Loader' and 'Loadall' vehicles. The JCB 'Backhoe Loader' is the iconic vehicle of the JCB fleet; JCB's website states that nearly half of all backhoe loaders sold round the world are JCBs. The 'Wheeled Loader' has a high load handling capability based entirely on the front shovel while the 'Loadall' vehicle features a telescopic arm that is used to handle loads with a reach of up to 20m. After the 'Backhoe Loader', the 'Loadall' is one of JCB's highest volume products. Together, these three vehicle families account for almost 80% of JCB vehicle sales.

JCB's internal data analysis **[S3]** indicates that, under road duty, the 'Backhoe Loader' achieved 1.21 litres per hour fuel saving and 7.9% CO_2 emissions reduction across all uses, while the 'Loadall' showed a fuel saving of 3.29 litres per hour and CO_2 emissions reduction of 13% across all uses. The Product Innovation Director of JCB confirmed this data and stated

"*the technologies which were first developed in the JCB Transmissions / LU collaborative Eco Drive Line [ECO-DL] project of 2016/2017 are now being introduced into the drivelines of many Stage V emission JCB mid-range machines - including Backhoe Loaders, Loadalls, and Wheel Loaders … from January 2020, technical initiatives realised from the project have been integrated into all our axles for the agricultural market, with an approximate production volume of 700 per year."* **[S4]**

Commenting on an imminent launch for which ECO-DL project findings have been built into the development programme since 2017, he added:

"In Ql 2021, JCB will launch a new gearbox family for the construction industry which incorporates further ECO-DL initiatives taking the production volume to approximately 4,200 per year". **[S4]**

Impact 2: Achieved 100% gearbox reliability for world's leading Formula 1 race team, delivering championship-winning performances

The Loughborough team's research on tribo-dynamic numerical modelling of gear pairs **[R6]** has been one of the biggest influences on the Mercedes Grand Prix (MGP) gearbox design, leading to successive improvements in reliability that have been critical to winning the Formula 1 Constructors' and Drivers' Championships every year since 2017. The critical contribution was the incorporation of Loughborough's numerical codes for transmission modelling into the MGP simulation tools. These provided essential knowledge of the dynamic loading on gear teeth during power transmission, leading to clarity about gearbox failure modes and operation limits.

Gearbox reliability is of primary importance in Formula 1 racing. Repairs mean lost track time and current race rules impose grid penalties if a replacement gearbox is used. Catastrophic raceday failures prevent race completion which means lost championship points.

As well as enhancing reliability, our research has led to additional gains through reduction in oil volume, which decreases gearbox mass and oil churning losses, and ultimately contributes to better performance of the car overall. This is significant in a context where gearbox reliability improvements generally come with increased weight.

The Chief Engineer of Mercedes Grand Prix reported that:

> *"Not only has the Loughborough research been a key aspect for Mercedes Grand Prix (MGP) to understand how to design the gearbox to prevent failures, it has also proved surprisingly useful for improving laptime through reduction of churning losses".* **[S5]**

The Loughborough codes have influenced the gearbox design in each of the last 4 seasons, specifically optimising gear tooth geometry, gear ratios, and gearbox shaft properties and enhancing understanding of temperature and lubrication on gear performance.

The Mercedes Grand Prix Chief Engineer further stated that:

> "*All teams are understandably coy about the design details of their cars, but it is a matter of record that every year there are 5-10 gearbox penalties in the Championship (each incurring a 5-place grid penalty). Furthermore, any failure on track requires exhaustive technical review and a significant absorption of resources. For two whole seasons now, MGP have not suffered a single gearbox failure either in practice or during the race. This has been a significant factor in our success*" **[S5]**.

Since 2019, the gearboxes have also been used by the BWT Racing Point F1 team, who have not suffered failures either. The Chief Engineer concluded by saying:

> "*Our research collaboration with Loughborough has improved our understanding of gearbox design and contributed to a significant shift in gearbox reliability. As a result, we have obtained a competitive advantage compared to the other F1 Teams, providing a contributing factor to winning the Constructor's Championship every year since 2017*" **[S5]**.

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

S1 Aston Martin acknowledgement of Encyclopaedic project role in the new V12 design in the "Automotive Engineer" magazine
S2 Letter from Aston Martin Chief Engineer (at the time of the collaboration) confirming Source 1 and the role of the LU work therein
S3 Project Dissemination Memo – JCB Eco Axle – published within JCB and to Innovate UK as part of final project report
S4 Letter confirming the importance of the work undertaken in the Innovate UK Eco-Drive Line project now incorporated in JCB vehicles
S5 Letter from the Chief Engineer at Mercedes AMG F1 confirming the importance of the work undertaken with Loughborough