Institution: Loughborough University

Unit of Assessment: B12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Stability control algorithm research improves handling and safety for Jaguar Land Rover drivers

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

Drivers of more than 20,000 Jaguar supercharged cars sold worldwide since 2009 are enjoying handling and safety benefits as a direct result of research at Loughborough University. The active differentials control system in production on Jaguar's XF, XJ and XK vehicles is controlled by an algorithm developed at Loughborough. Funded by Jaguar Cars Ltd, the research from 2002 to 2006 was first adopted, after only minor changes, into the supercharged Jaguar XF programme released in 2009. The system is now also in the new F-type and is being extended, in a modified form, to Range Rovers, starting with the new Range Rover Sport.

2. Underpinning research (indicative maximum 500 words)

Research on techniques to support vehicle stability control has been a core theme at Loughborough for the past 25 years. The key research here considered theoretical capabilities and control authority from relatively expensive, overdriven differentials and also cheaper active limited slip differentials (ALSD). Although it has a more limited torque transfer capacity, the ALSD is capable of stabilising the vehicle's handling response and is the system now in use on Jaguar vehicles.

The research started within an MEng individual student project undertaken by Matthew Hancock (Loughborough undergraduate 1997 to 2002), sponsored by Jaguar Cars Ltd and under the supervision of Timothy Gordon, then Loughborough Professor of Vehicle Dynamics and Control (1985-2002). Matthew Hancock joined Jaguar Cars' research division after graduation and pursued the research via a part-time PhD with Loughborough, funded by Jaguar, under the supervision of Loughborough lecturer Matt Best (employed 1996 to date) and industrial supervisor Robert Williams (JLR). The resulting 2006 PhD thesis **[3.1]** includes most of the substantive elements of research on which the production systems are based. Although the protection of confidential and commercially sensitive material restricted publication, the fundamental research has been presented in respected engineering journals **[3.2]** and **[3.3]**.

The research required vehicle and differential modelling and validation, and the development of practicable control algorithms using model reference and classical control techniques, to regulate continuously the handling (understeer) behaviour and also maintain vehicle stability and hence safety. The measure of stability that can be recorded most easily on the vehicle is the rotation (yaw) rate through the corner. Thus in developing the techniques for test vehicles, the fundamental research was modified to use yaw rate alone to determine the control action, with its magnitude adapted according to vehicle forward speed and road surface friction. The vehicle development work also included integration and conflict resolution of the ALSD with a conventional brake-based yaw stabilisation system that is also invoked in the most extreme cases of loss of control. The control strategy built on underpinning research at Loughborough first published in 2000 **[3.4]** and 2002 **[3.5]**, where a linear optimal control is designed for a reference vehicle model and control is applied in two loops, both feedforward and feedback. This work was by Matt Best, Timothy Gordon and Ayao Komatsu (PhD student at Loughborough, 1999 to 2003).

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

3.1. Hancock, M.J., 'Vehicle Handling Control using Active Differentials,' *PhD Thesis*, Loughborough University, April 2006. Available at **https://dspace.lboro.ac.uk/2134/8075** or at request from Loughborough University.

3.2. Hancock, M.J., Williams, R.A., Gordon, T.J., and Best, M.C., 'Comparison of Braking and Differential Control of Interactive Yaw-Sideslip Dynamics', *Proceedings of the Institution of Mechanical Engineers, Part D (Journal of Automobile Engineering)*, 219

[D3] 309-27 (2005). DOI: 10.1243/095440705X6721.

3.3. Hancock, M.J., Williams, R.A., Fina, E. and Best, M.C., 'Yaw motion control via active differentials', *Transactions of the Institute of Measurement and Control*, 29 137-57 (2007). DOI: 10.1177/0142331207069489.

3.4. Komatsu A., Gordon T.J. and Best M.C., '4WS Control of Handling Dynamics Using a Linear Optimal Reference Model', *Proceedings of the 5th International Symposium on Advanced Vehicle Control (AVEC)*, Ann Arbor, USA, August 2000, pp 253-260. This output can be made available at request from Loughborough University.

3.5. Komatsu A., Gordon T.J. and Best M.C., 'Vehicle Path Optimisation using a Time-Variant Linear Optimal Reference Control', *Proceedings of the 6th International Symposium on Advanced Vehicle Control (AVEC)*, Hiroshima, Japan, September 2002, pp 93-98. This output can be made available at request from Loughborough University.

With the exception of R.A. Williams and E. Fina, both of Jaguar Land Rover, the other authors of the above outputs were affiliated to Loughborough University at the time of the research.

Key Grants:

- Jaguar Land Rover funded part-time PhD, £5,000, Matthew Hancock, 2002-2006.

Evidence of Research Quality:

- In 2002, Matthew Hancock won the national SET award for Best Mechanical Engineering Student for his work on this project.
- Where it has been possible to avoid commercial conflict, aspects of the algorithm have been published in journals and presented at conferences that are widely read / attended by both university academics and the global automotive industry.
- The system has been adopted for implementation on all Jaguar supercharged vehicles and will also be adopted in future Land Rover programmes.
- Patents issued: *Vehicle yaw control with tyre road friction estimator* (GB2428754), *Vehicle traction control using active limited slip differential* (GB2428755).

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

Electronic Stability Control (ESC) systems have been in use since around 2000 and have widely publicised benefits to the user. Since 2005 their impact has been measurable and Garrot **[5.1]** notes that single vehicle accidents have been reduced by 30-40%, whilst for 'loss of control' fatal accidents the reduction is up to 67%. With such obvious benefits to consumers, many manufacturers are fitting ESC systems as standard. EU legislation has required all HGVs and coaches to be fitted with ESC since 2010 and all cars must have ESC by 2014. Critically, most ESC systems use the Antilock Brake System (ABS) brake actuators already fitted to vehicles. These act discretely, at or near the point of loss of control of the vehicle, braking the vehicle as well as correcting its yaw rate but producing a noticeable intervention to the driver. Whilst the statistics prove the accident prevention benefits of these systems, the motoring press dislike the intervention and in most cases the system can be turned off by the driver.

The advantage of ALSD is that yaw rate control is provided continuously, and imperceptibly, to the driver. The yaw correction is provided by left/right drive torque redistribution at the rear wheels, so no braking is applied in most driving scenarios. The torque transfer capacity is limited and the Jaguar system is implemented in conjunction with a brake-based system that intervenes in the most extreme scenarios. For drivers of the very powerful supercharged cars that adopt this system, however, maintaining continuous control over the wider range of yaw behaviour of the car is seen as a significant advantage, making the potentially fatal consequences of the driver turning off the ESC less likely.

Following the vehicle and simulation based research carried out by Matthew Hancock within his PhD research, the system was adopted on Jaguar's X250 programme for the 2009 XFR (the supercharged variant of the XF) **[5.2]**. The control software passed through company homologation, quality and reliability processes to satisfy BS EN ISO9001:2008 and therefore attracted rigorous scrutiny and some modification for mass production.

ALSD does not operate independently of other software on the vehicle. For example, vehicle speed and yaw rate sensing software and road friction estimation are required for its use; these were not developed as part of this research. However, the vehicle and differential system modelling, supporting simulation work and subsequent structural design of the controller is specifically relevant. The fundamental operation of Jaguar's control software is substantially that which appears in Hancock's PhD. The research is now in production and contributes very substantially to the overall success of the ALSD on the production vehicle, providing "a major contribution to the handling performance and stability control refinement of these vehicles" **[5.2]**.

Since the XFR was launched to critical acclaim (*What Car* voted the XF car of the year in 2008, and best executive car in 2011), Jaguar has introduced the ALSD system onto all new supercharged variants of its range (XF, XK and XJ). To date approximately 20,000 of these vehicles have been sold worldwide.

Jaguar is not the only car company offering differential control (BMW offer a similar system on the M5) and, as stated, not all of the ESC benefits of Jaguar's supercharged cars pertain to the ALSD system. However, the system does introduce benefits for drivers that users have praised. Press reviews note the beneficial handling qualities as well as stability of the ALSD. Comments have included:

"The diff control can shunt torque across the axle, promoting better stability, better response". **[5.3]**

"Putting the power to the ground further than ever is the new Active Differential Control (ADC), which is an electronically controlled alternative to the traditional mechanical limited-slip differential, with far more subtle control strategies … Its subtle control strategies optimize traction at each wheel, improving acceleration on low-grip surfaces but also potentially improving stability when required." **[5.4]**

"Active Differential Control technology … uses a multiplate clutch to vector torque to the driven wheel with the most grip. Allied to the **ABS** and stability control, this allows for the ultimate in traction and precision both mid-corner and at its exit." **[5.5]**

"Grip is barnacle-like, and when the driver exceeds the car's limits — which requires determination — he'll feel the diff helping to keep the front of the vehicle ahead of the stern." **[5.6]**

The system is now being used on the new F-type (unveiled at the Paris Motor Show in September 2012) and is in the process of being extended to Range Rovers, starting with the new Range Rover Sport.

When assessing domestic economic impact, it is useful to know that all Jaguar Land Rover vehicles are built in the UK.

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

To corroborate the impact the following sources can be made available to the panel at request:

5.1. Garrot, R. 2005, 'The Status of NHTSA's ESC Research' http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/VRTC/ca/esc/NHTSA_ESCupdate2005Apr19.pdf

5.2. Signed statement from Head of Vehicle Dynamics, Jaguar Land Rover is available from Loughborough University at request.

5.3. EVO magazine, March 2009, 'Review of Jaguar XFR and XKR' http://www.evo.co.uk/features/features/233661/jaguar_xfr_and_xkr.html

5.4. Automotive Addicts, September 2009, '2010 Jaguar XKR Supercharged Convertible Review and Test Drive' http://www.automotiveaddicts.com/7034/2010-jaguar-xkr-supercharged-convertible-review-

test-drive

5.5. Auto Spectator, November 2011, ’ 2012 Jaguar XK & XKR Coupe & Convertible Review’ http://www.autospectator.com/cars/models/2012-jaguar-xk-amp-xkr-coupe-amp-convertible-review-pictures-features-specs

5.6. Car and Driver, September 2011, ‘2012 Jaguar XKR-S’ http://www.caranddriver.com/reviews/2012-jaguar-xkr-s-first-drive-reviews