Institution: Queen's University Belfast		
Unit of Assessment: 12		
Title of case study: Towards Zero Emission Public Buses		
Period when the underpinning research was undertaken: 2009 – 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:**
Dr G Cunningham Prof R Douglas Dr J Early Dr R Kee Dr B Smyth Dr D Soban	Senior Lecturer Professor Reader Senior Lecturer Lecturer Senior Lecturer	1997 - Current 1985 - Current 2007 – Current 1989 – 2017 2013 – Current 2010 - Current
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

QUB in collaboration with Wrightbus have developed best in class low and zero emissions technologies, and played a key role in decarbonizing UK and international public transport. Since 2014, 1000 QUB technology driven powertrains have continued to reduce CO_2 emissions by 250,000 per year on London bus routes alone. Powertrain modelling and lifecycle modelling research at QUB has played an integral role in the recent GBP66,000,000 investment by Translink for 100 low emission battery electric and hydrogen vehicles, and pioneering research by the newly renamed QUB Bamford Technology Centre continues to lead the way along the road to zero.

2. Underpinning research

QUB has a distinguished track record in engine simulation. The focus has broadened from modelling conventional internal combustion engines in the mid-1990s to modelling the complete powertrain system in recent years. Powertrain simulation is complicated by the large number of rapid variations in parameters over a typical drive cycle. Much research effort has been invested at QUB over the last 20 years to construct accurate models with a strong physical basis. This has been underpinned through state-of-the-art engine test cells to characterise performance over complete drive cycles, which has established confidence in models through a research culture of rigorous experimental validation.

In 2005, a collaborative research project began with Wrightbus to develop modelling architectures for full hybrid powertrains [Douglas]. This work focussed on the construction of high-fidelity models of key system components, including batteries, motors and inverters. These models were integrated into design tools and extensively tested and validated against drive cycle data from testing at Millbrook facilities. This validated modelling capability was a breakthrough step in the design of hybrid vehicle powertrains, which for the first time delivered a tool to predict the instantaneous state of the engine in response to variations in system design and component selection This was foundational for the development of the hybrid powertrain for the 'New Bus for London [Douglas]. Previous modelling methods relied heavily on global or averaged system characteristics, such as total fuel consumption over a fixed driving extent, and had limited ability to account for rapid fluctuations in powertrain inputs, which typify conditions experienced on urban routes. The QUB team achieved a breakthrough with the capability to replicate rapid transients in powertrain inputs and responses by the physical modelling of individual components.

Building on these successes and the challenges of the Next Generation Hybrid Electric Vehicle and its increased complexity, the QUB team focused on simulation flexibility [**R1:** Early, Kee]. New modelling approaches were developed to allow changes to system configuration to be evaluated rapidly, allowing greater potential of the hybrid systems to be realised for fuel and emissions reductions [**R2, R3:** Early, Cunningham, Douglas]. This work was supported through the Innovate UK Low Emission Vehicle Systems programme (IDP13, Douglas, Early) and resulted in Low Carbon Vehicle certificates being awarded to both the single and double deck variants of the HEV-96V bus (shown below).

Alongside fundamental powertrain research, QUB has led in the development of accurate lifecycle models [**R4**: Soban, Smyth] [**R5**: Douglas, Early]. These tools allow accurate comparisons to be made between alternative powertrain technologies, in terms of ownership costs, running costs and lifecycle emissions to achieve commercially viable, low carbon solutions that will be adopted by fleet operators.

This collaboration has resulted in the formation of the GBP5,000,000 Sir William Wright Technology Centre (W-TECH) [Douglas], launched by the Commissioner for Transport for London, Mike Brown, in 2017, and recently renamed the Bamford Technology Centre after the successful takeover of Wrightbus in 2020. This is the world's first technical centre of excellence solely focussed on public bus technology, and has become a focal point for future technologies within the sector. This encompasses research in future driveline development, advanced control systems, vehicle light-weighting and structural design, thermal and lifecycle analysis as well as bus safety. The centre works with partners internationally, recently concluding work in conjunction with Kowloon Motor Bus Company (KMB) on safety aspects of advanced driver assistance systems [**R6**: Douglas, Early].

In 2019, the Centre embarked on the Next Generation Electric Vehicle programme (IDP14, Douglas, Early, Cunningham), funded by Innovate UK. This builds directly on the modelling expertise retained in the Centre [**R1- R6**], where development work is continuing to develop the first UK produced fully electric powertrain. Increasingly, the lifecycle modelling work carried out by QUB [**R4**: Soban, Smyth] [**R5**: Douglas, Early] forms an integral part in public transport policy making, identifying routes which offer the maximum advantages in terms of fuel economy, emissions and environmental impact. Most recently (December 2020), Wrightbus and QUB [Douglas, Early] have been successful in gaining funding from the Advanced Propulsion Centre for an Advanced Route to Market Demonstrator fuel cell electric vehicle, due to launch in September 2021. The Centre continues to lead the way in rapidly bringing novel, advanced low and zero emission drivetrain technology from academic research to market.

3. References to the research

R1: Stevens, G., Murtagh, M., Kee, R., Early, J. & Best, R., 2017, 'Development of a vehicle model architecture to improve modeling flexibility', SAE International Journal of Engines, vol. 10, no. 3, 2017-01-1138. https://doi.org/10.4271/2017-01-1138

R2: Murtagh, M., Early, J., Stevens, G., Cunningham, G., Douglas, R. & Best, R., 2019, Modelling and Control of a 96V Hybrid Urban Bus. in *WCX SAE World Congress Experience 2019: Proceedings* . SAE Technical Papers, WCX SAE World Congress Experience, Detroit, United States, 09/04/2019. https://doi.org/10.4271/2019-01-0354

R3: Stevens, G., Early, J., Cunningham, G., Murtagh, M., Douglas, R. & Best, R., 2019, 'Multi-fidelity validation algorithm for next generation hybrid-electric vehicle system design', Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. https://doi.org/10.1177/0954407018825015

R4: Harris, A., Soban, D., Smyth, B.M. & Best, R., 2018, 'Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies', *Renewable and Sustainable Energy Reviews*, vol. 97, pp. 569-579. https://doi.org/10.1016/j.rser.2018.08.045

R5: Doyle, D., Harris, A., Douglas, R, Early, J. & Best, R., 2020, “Hydrogen Fuel Cell Buses: Modelling & analysing suitability from an operator and environmental perspective”, SAE Technical Papers. 2020-01-1172. https://doi.org/10.4271/2020-01-1172

R6: Blades, L., Douglas, R., Early, J., Lo, C.Y. & Best, R., 2020. “Advanced driver-assistance systems for City Bus Applications”. SAE Technical Papers. 2020-01-1208. https://doi.org/10.4271/2020-01-1208

4. Details of the impact

Air quality is a major public health concern, particularly in built up urban areas, and recent years have seen the expansion of the number of low emission zones throughout the UK, as well as the introduction of an ultra-low emission zone in central London. In the “Road to Zero” strategy document, the UK government has laid out its ambition for all new cars and vans to be effectively zero emission by 2040, as well as schemes to encourage low emission public transport. Buses play a vital role in reducing emissions; one double-deck bus can potentially replace 75 cars. In inner cities, the stop/start conditions and slower speeds mean that older diesel vehicles in particular can emit significant levels of local pollutants.

Hybrid electric vehicle architectures are key in this transition to ultra-low and ultimately zero emissions solutions. Building on over 20 years of powertrain modelling research, Queen’s University Belfast have developed advanced hybrid powertrain modelling technology which is integral to thousands of low emission hybrid vehicles currently in service around the world.

In collaboration with Wrightbus, Queen’s University began work on developing state of the art system modelling approaches for hybrid vehicles on the development of the New Bus for London powertrain. Director of Engineering for Wrightbus, states *“This modelling work was key in enabling us to meet extremely demanding technical specifications, and the direct result of this research was a best in class system in terms of fuel economy and exhaust emissions. Subsequently Wrightbus won the contract to supply 1000 buses of this type to Transport for London, commencing in 2012".* [**S1**]

The success of the London Bus project led directly to the GBP3,200,000 Innovate UK funded project “Next Generation Hybrid Bus” (NextGenHEV). This project led to further innovations in powertrain system modelling, with the evolution of flexible systems modelling architectures which enabled rapid evaluation of candidate hybrid vehicle systems and components. Director of Engineering for Wrightbus states that *"This modelling architecture has been integral to the development of our flagship hybrid electric vehicles, the StreetLite and StreetDeck Next Generation Hybrid buses, supporting the design of the overall system configuration, component sizing, as well as the "on vehicle" control system".* [**S1**]

The driveline development ultimately led to both the single deck (StreetLite) and double deck (StreetDeck) variants being certified to low carbon emission bus status by the Low Carbon Vehicle Partnership [**S2-S4**]. This certification confirms the achievement of a 35% well-to-wheel greenhouse gas saving in comparison to the Euro V diesel engine baseline; this equates to a saving of 25,000 kg of equivalent CO_2 per year for a single average London Bus. Additionally, the "StreetDeck" double decker variant of the next generation hybrid bus has been awarded an Ultralow Emission Bus Certificate, with similar status pending for the single deck version. In competitive benchmark testing, the double decker StreetDeck bus achieved 15% better fuel economy than its nearest rival [**S4**], with the single deck variant, the StreetLite, achieving a 6% improvement [**S3**]. Although it is an early stage in the lifetime of this next generation vehicle, Wrightbus have already sold over 100 HEV single and double deck vehicles as a direct result of this partnership with Queen's University. These vehicles are currently carrying thousands of passengers daily on a number of high-profile routes in Oxford and London [**S1, S5**].

Beyond the UK, the hybrid powertrain system & design approaches developed during the Next Generation Hybrid Bus project have opened up new opportunities to export this technology internationally. Wrightbus received a breakthrough order for 5 StreetDeck for Monterrey City, Mexico, which entered service in 2017, which marked the first introduction of Euro 6 standard vehicles in Latin America [**S1, S6**]. Recently Wrightbus have secured a series of multi-million pound orders for Hong Kong to deliver 584 vehicles over a two-year period; significantly this included a further 50 StreetDeck buses, which is the first time that Wrightbus integral powertrain vehicles have been delivered to this long standing customer [**S1**, **S6**].

Alongside the research and development effort on hybrid powertrains, the research carried out by Queen's on full vehicle lifecycle models has been another key enabling factor in exploiting these potential export opportunities [**S1, S6**]. Account Manager for Wrightbus International explains, *"These tools are now key components in our decision making process.. this equips us with the ability to offer bespoke, commercially viable low carbon transport solutions to international transport operators".* [**S1, S6**]. Queen's University have used this lifecycle modelling work, alongside in-service fleet monitoring, to support a number of tender processes, including in Santiago Chile and Canberra Australia. As an example of the implementation of these tools, Account Manager for Wrightbus International explains: *"Recently we have developed a customised StreetDeck bus for Santiago Chile, where the technology represents huge potential savings in carbon emissions and harmful pollutants in comparison to the city's predominantly Euro 2 and Euro 3 bus fleets".* [**S1, S6**]. According to European Emissions standards, a Euro 6 rated engine produces 92% lower NOx emissions than its Euro 3 predecessor, highlighting the transformative effect this technology can have on air quality in built up urban environments as soon as the bus starts rolling. Account Manager for Wrightbus International comments further on the importance of these technology milestones on potential future exports: *"Set against a backdrop of increasing concerns about pollution and its implications on health and global warming, these are hugely significant developments for Wrightbus, which are expected to yield new international orders for the company of between £10,000,000 and £15,000,000. This represents an important stream of exports for the local economy, as well as building the company's brand value overseas."* [**S1, S6**].

Capitalising on this hugely successful collaborative research relationship, the GBP5,000,000 Sir William Wright Technology Centre (W-TECH) was formally launched in 2017. This has directly resulted in the generation of 8 high value postdoctoral research and development jobs.

The Centre has attracted leading researchers from across the globe, including secondments for engineers from some of the world's largest public transport operators, including Kowloon Motor Bus (KWB) in Hong Kong [**S1, S7**]. Renamed as the Bamford Technology Centre following Wrightbus' change of ownership in 2020, building on the modelling skills and experience retained at QUB. The powertrain and lifecycle modelling research is increasingly being implemented by public bodies in their decision making process relating to decarbonising public transport. Most recently, this modelling methodology played an instrumental role in Translink's decision to invest GBP66,000,000 in a fleet of 80 battery vehicle and 20 Hydrogen fuel cell vehicles, along with supporting infrastructure [**S1, S8**]. The Centre continues to ensure that the UK leads the way in driving technology towards zero net emission for public transport.

5. Sources to corroborate the impact

S1: Director of Engineering, Wrightbus/Bamford Bus Company Letter of Support
S2: Low Emission Bus Scheme Certificate, StreetDeck HEV
S3: Low Emission Bus Scheme Certificate, StreetLite HEV
S4: Ultra Low Emission Bus Scheme Certificate, StreetDeck HEV
S5: Group Chief Engineer, Go-Ahead Group
S6: Regional Account Manager, Wrightbus International Letter of Support
S7: Contracts Manager ADL Hong Kong, previously Head of Engineering and Technical Training Kowloon Motor Bus Company (KMB) Hong Kong
S8: General Manager Engineering, Translink