ULTRA-CAPACITOR BASED KINETIC ENERGY RECOVERY SYSTEM FOR HEAVY GOODS VEHICLES

D. AINALIS

Research Associate in the Centre for Transport Studies at Imperial College London. Obtained his Ph.D. in Mechanical Engineering from Victoria University, Australia, in the fields of vehicle dynamics and distribution vibration analysis and simulation.

P.E. ACHURRA-GONZALEZ

Research Associate in the Centre for Transport Studies at Imperial College London. His research interests are focused on the development of mathematical models for freight cargo routing, resilience, and transport emissions.

A. GAUDIN

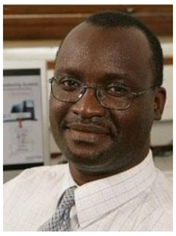
Double Master's degree student at ENSTA ParisTech and the National University of Singapore. Antoine is currently working on a Master's thesis focused on maritime carbon pricing.

J. M. Garcia de la Cruz

Aeronautical Engineer from the Universidad Politécnica de Madrid, and Ph.D. obtained from Imperial College London. Marcos worked on aerodynamic drag reduction and energy recovery systems for hauling vehicles.

P. ANGELOUDIS

Senior Lecturer in Transport Systems and Logistics at Imperial College London. He is the Director of the Transport Systems and Logistics group within the Centre for Transport Studies.



W.Y. OCHIENG

Professor Ochieng is the Head of the Centre for Transport Studies at Imperial College London. He holds the Chair of Positioning and Navigation Systems and is the Director of the Engineering Geomatics Group.

M.E.J. STETTLER

Lecturer in Transport and Environment at Imperial College London. He is also the Director of the Transport & Environment Laboratory within the Centre for Transport Studies.

Abstract

The Climate Change Act 2008 commits the UK to reduce the Greenhouse Gas emissions by 80% by 2050 relative to 1990 levels. While Heavy Goods Vehicles and buses contribute about 4% of the total Greenhouse Gas emissions in the UK, these emissions only decrease by 10% between 1990 and 2015. Urban areas are particularly susceptible to emissions and can have a significant impact upon the health of residents. For Heavy Goods Vehicles, braking losses are one of the most significant losses. A Kinetic Energy Recovery System can help reduce these emissions, and increase fuel efficiency by up to 30 %. This paper describes an InnovateUK funded project aimed at evaluating the technical and economic feasibility of a retrofitted Kinetic Energy Recovery System on Heavy Goods Vehicles through an operational trial, controlled emissions and fuel tests, and numerical modelling. A series of preliminary results using a numerical vehicle model is compared with operational data, along with simulations comparing the fuel efficiency of a Heavy Goods Vehicle with and without the KERS.

Keywords: Low emission transport, KERS, ultracapacitors, Heavy Goods Vehicles.

1. Introduction

The Climate Change Act 2008 commits the UK to reduce Greenhouse Gas (GHG) emissions by 80% by 2050 relative to 1990 levels (UKP, 2008). Currently, Heavy Goods Vehicles (HGVs) and buses contribute about 4% of the total GHG emissions in the UK (DfT, 2017a). While total GHG emissions decreased by 38% between 1990 and 2015 (DBEIS, 2017), emissions from HGVs only reduced by 10% over the same period (DfT, 2017b). These were driven by reductions in freight kilometres and goods lifted (DfT, 2018) rather than engine efficiency improvements which have been constrained by increasingly strict Euro emissions standards designed to reduce tailpipe emissions of Nitrogen Oxides (NO_x) and Particulate Matter (PM) (Sharpe et al. 2011).

Freight emissions are also relevant in the context of urban transport, where noxious emissions impact upon the health of the population. In 2010, HGVs accounted for 1.9% of CO_2, 7.6% NO_x and 3.1% PM_{10} emissions in London (TfL, 2014), where the total mortality burden from poor air quality is equivalent to 9500 deaths per year representing an estimated economic cost of up to £3.7 bn (Robinson, 2017; LoCITY 2016). Mohamed-Kassim and Filippone (2010) determined that up to 50% of the energy delivered by the engine in urban environments is dissipated as heat when braking. As such, “braking losses” can be considered to be the single most important contributor to vehicle inefficiency, followed by “rolling resistance”, “aerodynamic losses”, “auxiliary loads” and “drivetrain losses” (NASEM, 2015). A Kinetic Energy Recovery System (KERS) installed in an HGV operating in urban cycles could harvest the braking energy and increase the vehicle fuel efficiency by up to 30% (Bauman and Kazerani, 2008).

1.1 Overview of the KERS-URBAN Project

In 2017, a consortium was formed to undertake the first study to evaluate the energy and emissions benefits of an ultracapacitor-based KERS under operational duty cycles and in controlled vehicle emissions testing under the project title KERS-URBAN. The consortium includes two fleet operators in Howdens Joinery Ltd and Sainsbury’s Supermarkets Ltd, the KERS provider Alternatech Ltd, and the Centre for Transport Studies at Imperial College London. This project is funded by Innovate UK and the Office for Low Emissions Vehicles as part of the Low Emissions Freight and Logistics Trial (https://left.trl.co.uk/). This manuscript describes the research plan for the KERS-URBAN project, including the operational trial of two different architectures of an electric hybrid KERS retrofitted onto 18-tonne rigid vehicles and 44-tonne articulated vehicles, and some preliminary modelling and analysis with operational telematics data to examine the potential fuel savings.

2. Methodology

This study evaluates the technical and commercial feasibility of a retrofit ultracapacitor-based KERS that assists the original diesel engine during acceleration. The project employs a three-pronged approach to evaluate the two KERS architectures; operational testing, controlled emissions (and noise) testing, and numerical modelling of the HGV-KERS. For the operational testing, baseline telematics data collection began in January 2018 and the operational data collection trial of the KERS will comprise a 12-month period from July 2018 to July 2019. Control vehicles will be tracked over the same period to calculate the relative fuel consumption savings. Event-driven and time-resolved telematics data will be used to evaluate the efficacy of the KERS over different duty cycles and routes.

2.1 Heavy Goods Vehicles and KERS Architecture Description

Three different HGV types will be used to evaluate the retrofitted KERS architectures, including a rigid 18-tonne vehicle, a 44-tonne tractor and Urban trailer combination, and a 44-tonee tractor and Tall-boy trailer combination. The KERS retrofits are supplied and installed by Alternatech Ltd, and are based on KERS developed by Adgero SaS. The systems use a YASA 750R (100 kW) electric motor that produces a maximum torque of 790 Nm, and three Skeleton Technologies ultracapacitors (170 V, 1.26 Ah). The control system has been designed and developed by Adgero. Ultracapacitors have been selected as the preferred energy storage system due to their higher specific power, greater efficiency, and longer lifetime in comparison to batteries (Odhams et al., 2010). They are consistently the lightest and most compact choice for electrical energy storage in a system that is expected to transfer its full energetic capacity within a relatively short timeframe (1 – 10 s). This is the typical time range of the acceleration/deceleration profile in the urban cycles targeted to benefit the most from a KERS (Barlow et al., 2009).

A conceptual illustration of the two parallel KERS architectures used in this study are presented in Figure 1. In both architectures, the electric motor/generator switches between converting electrical energy into kinetic energy (motor) and converting vehicle kinetic energy into electricity that is stored in the ultracapacitors (generator). Figure 1 (left) illustrates the direct parallel hybrid KERS architecture installed on the 18-tonne rigid vehicles; the electric motor-generator is attached to the prop-shaft and connects the gearbox to the wheels. Figure 1 (right) demonstrates the layout of the through-the-road parallel hybrid KERS architecture installed onto the trailers; the electric plant provides power through a separate axle to the diesel engine. This alternative architecture for the articulated vehicles was necessary due to a lack of available space on the tractors.

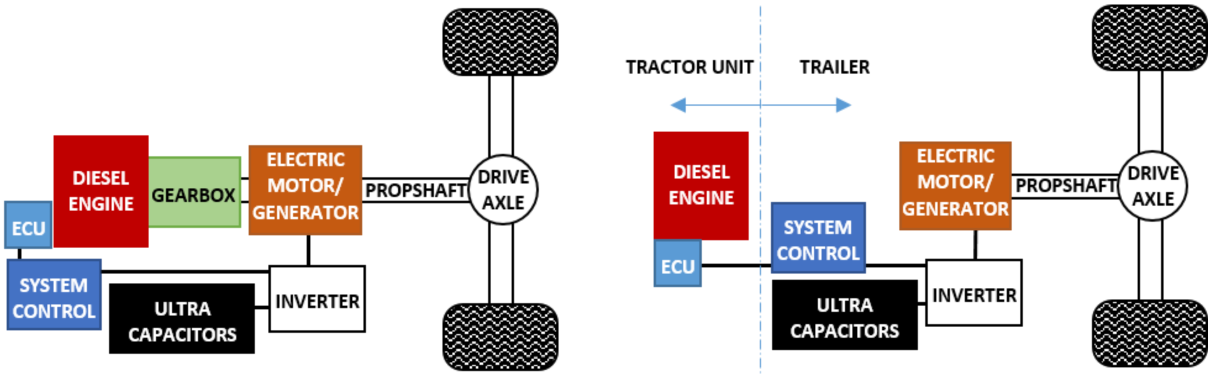


Figure 1: The retrofitted KERS architectures under investigation; the first system (left) is retrofit onto the original vehicle propshaft through thegearbox in a direct-parallel hybrid, and the second (right) is installed on a modified axle of a through-the-road-parallel hybrid.

In total, twenty vehicles will be retrofitted with the two KERS architectures. The direct-parallel hybrid KERS is installed onto ten 18-tonne 235 bhp Mercedes Antos 1824 rigid vehicles with a 4 × 2 axle configuration, all operated by Sainsbury's Supermarkets Ltd. The second, through-the-road parallel hybrid KERS will be installed on two different trailer types. Six Urban 10.3 m tandem axle trailers (10.3 x 3.7 x 4.2 m) and four Tall-boy 13.6 m tri-axle trailers (13.6 x 2.55 x 4.96 m), all operated by Howdens Joinery Ltd. The trailers are not assigned to fixed tractors, and are pulled by either a 449 bhp DAF CF MX-11 (4 × 2 axle configuration), or a 462 bhp DAF CF MX-13 (6 × 2 axle configuration).

2.2 Data Collection and Experimental Testing

A 12-month operational trial of the KERS will form the basis of the study to evaluate the efficacy of these systems. To provide a baseline comparison, the two fleet operators will provide an additional thirty-seven vehicles (18 from Sainsbury's Ltd and 19 from Howdens Joinery Ltd) to be monitored throughout the trial period. A sample of the geographical coverage of routes travelled by the vehicles from the vehicle telematics is presented in Figure 2.

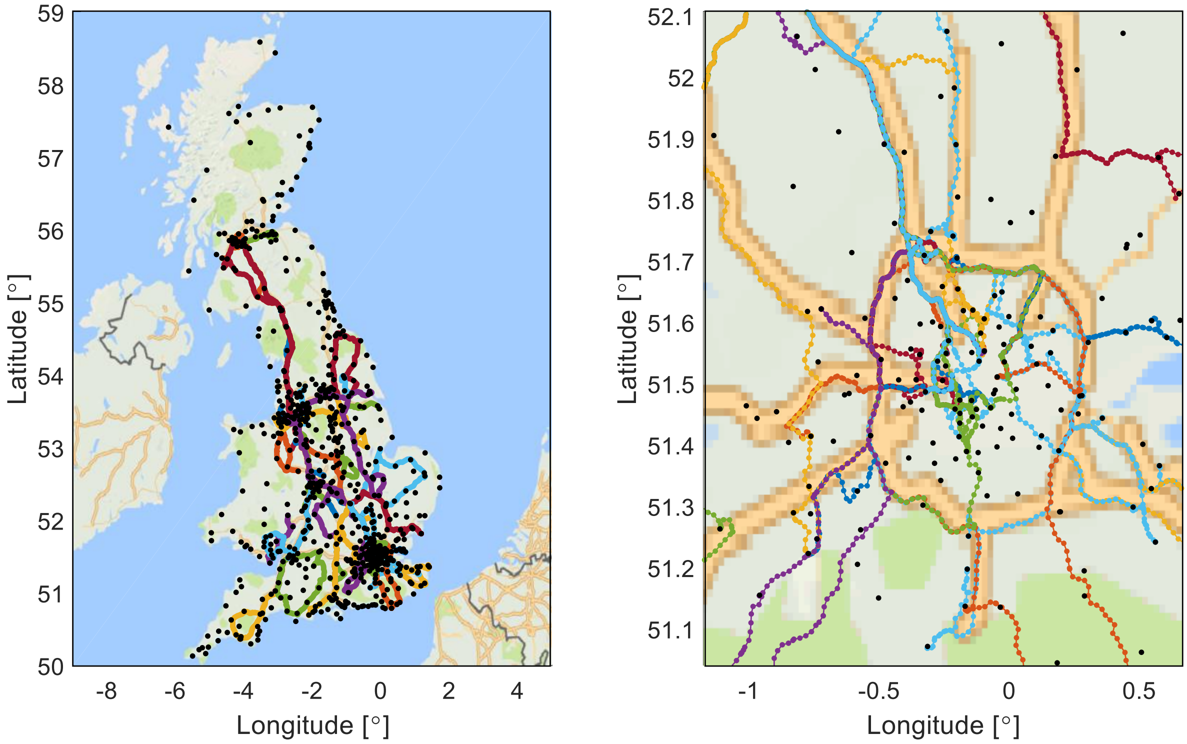


Figure 2: Geographic coverage of routes and sites obtained from the telematics operational data across the UK (left), and around Longon (right) from sample telematics data obtained during February 2018.

In addition to the operational trials, controlled emissions tests will be conducted for each KERS architectures and control vehicles as per the protocol outlined by the Low Carbon Vehicle Partnership (LowCVP, 2018). Track tests using portable emissions measurement systems over a range of drive cycles (long-haul, regional delivery, urban delivery, and congested city centre (EC, 2017)) will also be conducted. During these tests, noise measurements will also be undertaken to investigate whether the KERS architectures provide a noise reduction compared to the control vehicles.

2.3 Vehicle Modelling

From the controlled tests, accurate engine fuel efficiency and emissions maps will be established and used in conjunction with the data obtained from the operational trial to improve the accuracy of the vehicle models developed using the Advanced Vehicle Simulator (ADVISOR). ADVISOR is a MATLAB/Simulink simulation program for the analysis of fuel efficiency and emissions performance of vehicles with hybrid powertrains (Markel et al., 2002). The vehicle models developed in ADVISOR will be used to optimize the KERS components and algorithms to minimise fuel consumption, GHG emissions, delivery routes, and installation and operational KERS costs. The HGVs included in this study will all be modelled in ADVISOR; however, this paper only presents results using the modelled DAF CF MX-13.

Heavy goods vehicle model

Several vehicle parameters need to be incorporated into ADVISOR to obtain accurate results. Without the controlled tests, an accurate fuel efficiency map is not available for implementation; however, a DAF CF 75 (EURO V) engine map has been implemented for preliminary investigation (Stettler et al., 2016). Vehicle parameters have been obtained from the manufacturer's product specification sheets, and from discussions with the consortium partners and fleet managers. The DAF CF MX-13 is the vehicle modelled in this study and, including the tractor and trailer, has a total mass of 15,000 kg.

KERS model

The KERS has been modelled based on product specification sheets and from conversations with the supplier company Adgero. Due to commercial sensitivities, some details of the KERS system have not been disclosed. An outline of the modelled hybrid powertrain is given in Figure 3. The total mass of the KERS components is approximately 250 kg. One important aspect that can be discussed is the control strategy employed by the Adgero KERS to manage the power distribution. There are three basic conditions for the system and are handled as follows. Firstly, during braking the kinetic energy is converted via the electric motor up to its limit of 100 kW, with the remaining energy dissipated via the brakes. The next case is during cruising where, while the acceleration is negative, the drive train is required to produce power to overcome the aerodynamic drag and rolling resistance of the vehicle. This power will be provided entirely by the diesel engine (i.e. the KERS is not operational). The last case is acceleration, where the electric motor will produce the requested torque up to its limit of 750 Nm, and any additional required power is provided by the diesel engine. It should also be noted that the KERS strategy does not affect the idling of the engine (i.e. no stop / start technology).

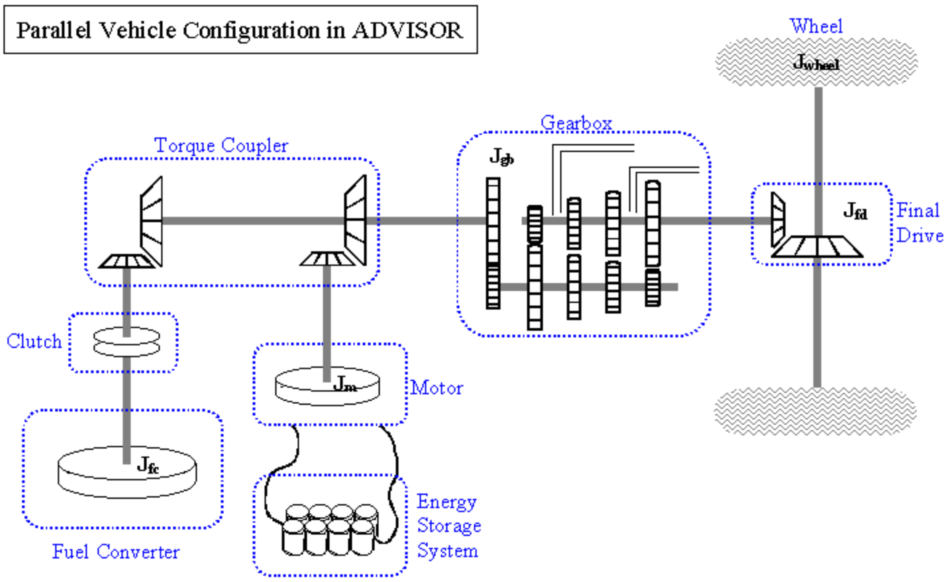


Figure 3: Conceptual illustration of the hybrid vehicle powertrain to model the KERS in ADVISOR (Markel et al., 2002).

Drive Cycles

Three actual driving cycles are obtained from the operational telematics data, along with the measured fuel consumption. These drive cycles are directly input into ADVISOR to simulate the modelled vehicle travelling along actual drive cycles. It should be noted that since the operational telematics data is event-driven, the vehicle speed between points was interpolated, resulting in a smoothed drive cycle that will underestimate the transient acceleration events.

3. Preliminary Results and Discussion

A series of preliminary results using the vehicle model based on a DAF CF MX-13 with and without the KERS are presented herein. First, a benchmark of the initial vehicle model developed in ADVISOR is compared to the obtained fuel consumption from the operational data. Three actual driving cycles are obtained from the operational telematics data, along with the measured fuel consumption. These drive cycles are directly input into ADVISOR to simulate the modelled vehicle travelling along actual drive cycles. The KERS is expected to be operational on all vehicles in mid-July 2018 and extensive results with the KERS on all HGVs will be presented at the symposium. Since the complete operational study with KERS and controlled vehicle emissions and fuel consumption testing are incomplete, the results presented in this paper are preliminary and may be subject to change.

3.1 Fuel Consumption Comparison between Operational Data and ADVISOR Model

This section presents an initial comparison between the operational telematics data and the numerical vehicle model developed using ADVISOR. The comparison is made from a Howdens DAF CF MX-13 with a Tall-Boy trailer, travelling along three different routes. The three drive cycles are obtained from the telematics data and used to provide an initial benchmark of the vehicle model developed (without KERS). The trips are denoted CYC_HOW_1 (67 km), CYC_HOW_2 (71 km), and CYC_HOW_3 (21 km), and the actual and simulated drive cycles and fuel consumption are presented in Figure 4, Figure 5, and Figure 6, respectively. A summary of the total actual and simulated fuel consumption is presented in Table 1.

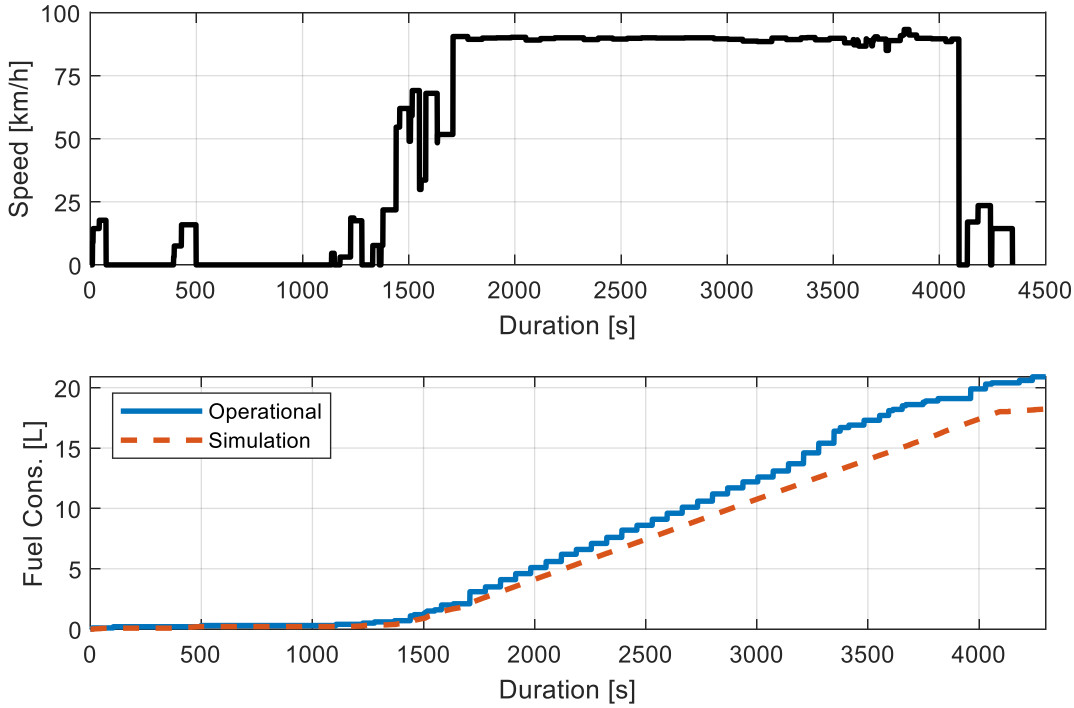


Figure 4: Operational drive cycle (top) and comparison of the operational and simulated fuel consumption (bottom) for CYC_HOW_1.

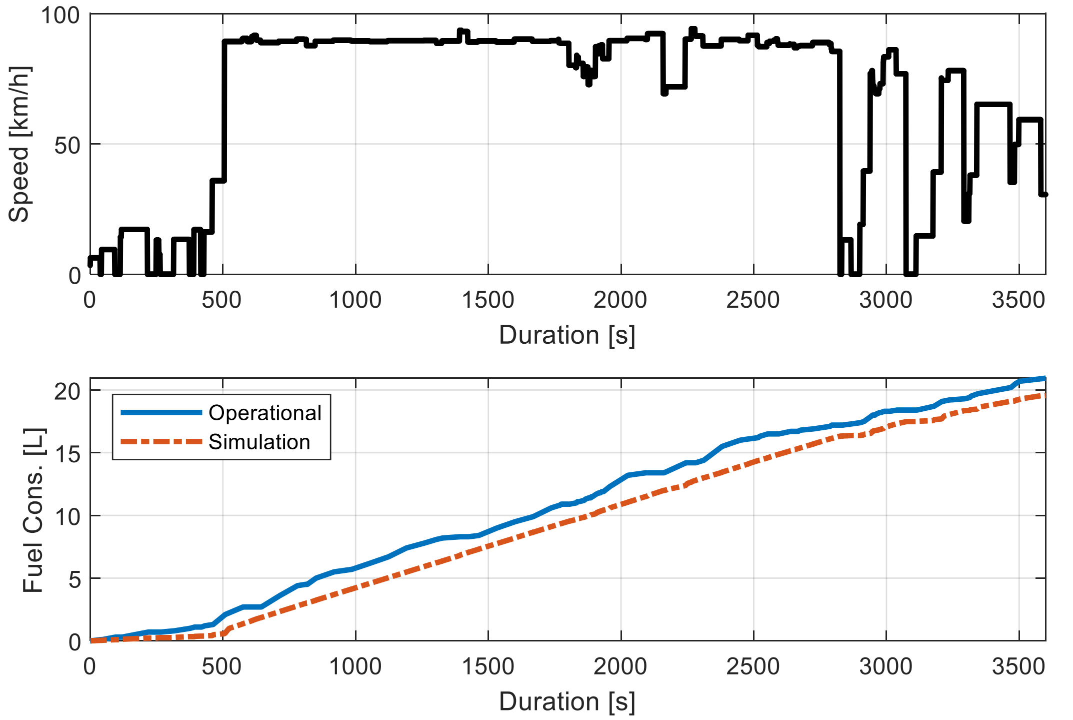


Figure 5: Operational drive cycle (top) and comparison of the operation and simulated fuel consumption (bottom) for CYC_HOW_2.

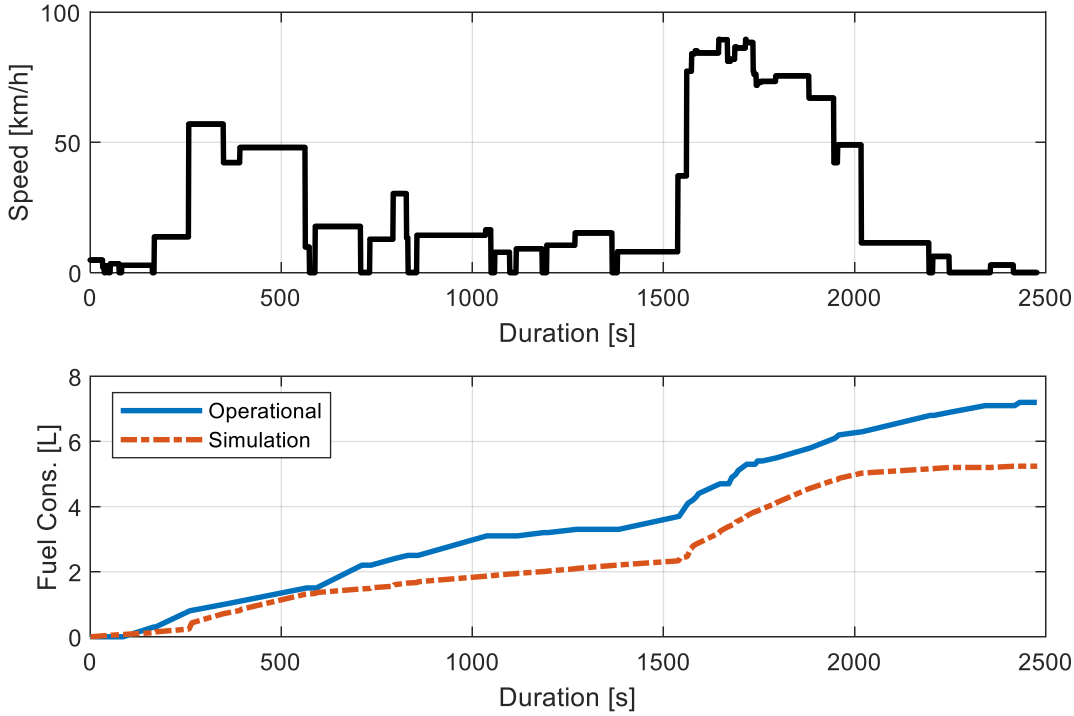


Figure 6: Operational drive cycle (top) and comparison of the operation and simulated fuel consumption (bottom) for CYC_HOW_3.

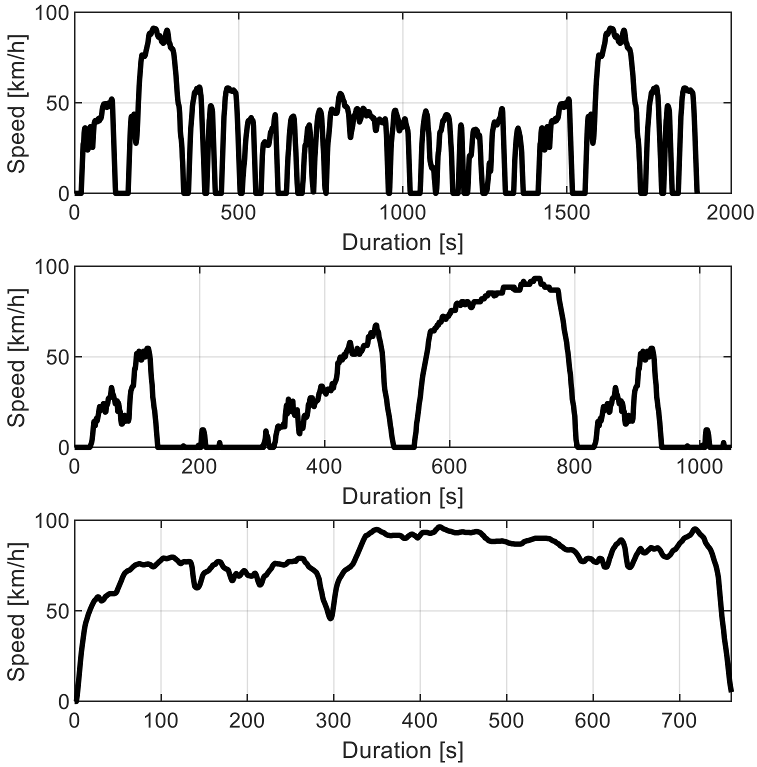
Table 1: Comparison of the fuel consumption across the three sample trips for a Howdens DAF CF MX-13.

	CYC_HOW_1	CYC_HOW_2	CYC_HOW_3
Operational Data [L]	21.1	21.4	7.2
Simulated [L]	18.3	20.1	5.2

From the results, it is evident that while there is some similarity between the operational and simulated fuel consumption, further work is required to improve the simulations and vehicle model to match the operational data. One issue is the lack of sufficiently high-resolution drive cycles, which is likely to underestimate the frequency of acceleration events. This can be seen in low simulated fuel consumption during transient sections of the drive cycles, where there is likely to have been significant variations in the vehicle speed instead of a series of constant-speed events. Several aspects of the ADVISOR model require improvement, most importantly the fuel efficiency maps. In addition, other factors such as road grade and elevation change are not yet included, but will be implemented in time for the symposium.

3.2 Simulated Fuel Consumption with KERS

Despite the current limitations of the model, it can be used to provide some initial indications of fuel consumption savings offered by the KERS on the DAF CF MX-13 HGV. Preliminary studies have revealed that similar KERS architectures can provide fuel consumption savings within 15 – 30 % depending on the drive cycle. A range of drive cycles are simulated with and without the preliminary hybrid powertrain model to investigate the potential range of fuel consumptions savings. Three different drive cycles are used to provide a preliminary evaluation of the fuel consumption savings due to the KERS. The first drive cycle is the FTP75 drive cycle (CYC_FTP) that is used for emission certification and fuel economy of vehicles. The Urban Dynamometer Driving Schedule Heavy Duty drive cycle (CYC_UDDS_HDV) represents city driving conditions and is used for heavy duty vehicle evaluation. Finally, the Highway Fuel Economy Test (CYC_HWFET) is a drive schedule used to evaluate the fuel economy of vehicles operating in highway conditions. All three drive cycles used to evaluate the performance of the KERS for the DAF CF MX-13 HGV are presented in in Figure 7.



(a)

Duration	1,877 s
Distance	17.77 km
Max Speed	91.25 km/h
Avg. Speed	34.12 km/h

(b)

Duration	1,060 s
Distance	8.90 km
Max Speed	93.30 km/h
Avg. Speed	30.40 km/h

(c)

Duration	765 s
Distance	16.45 km
Max Speed	95.27 km/h
Avg. Speed	77.77 km/h

Figure 7: Simulated drive cycles (a) CYC_FTP, (b) CYC_UDDS_HDV, and (c) CYC_HWFET used to evaluate the fuel consumption savings provided by the KERS on the DAF CF MX-13.

The simulated total fuel consumption for each of the drive cycles with and without the KERS architectures are summarised in Table 2. The KERS provides a reduction in fuel consumption across all three drive cycles examined, however the savings are greatly reduced for the highway schedule (between 12 – 15% on the urban drive cycles as opposed to 5% on the highway drive cycle). As expected, the ultracapacitor-based KERS provides the most benefit in fuel consumption savings in city or urban areas.

Table 2: Summary of the simulated fuel consumption with and without the KERS.

	CYC_FTP		**CYC_UDDS_HDV**		**CYC_HWFET**	
	Standard	*KERS*	*Standard*	*KERS*	*Standard*	*KERS*
Fuel Consumption [L/100 km]	40.02	34.20	40.27	35.43	28.48	26.88
Fuel Savings	-	14.55 %	-	12.03 %	-	5.61 %

4. Initial Conclusions and Future Work

This paper outlines a recently funded InnovateUK research project to investigate the economic and technical feasibility of the implementation of KERS on HGVs. Projections of the installation and maintenance costs of the architectures tested will be compared with the overall economic and environmental impact that the installation can deliver for various applications with HGVs. The research project aims to combine an operational trial, controlled testing, and numerical modelling to evaluate the KERS under a wide range of drive cycles, weather, and load conditions.

The numerical vehicle model was compared with the initial operational telematics data obtained to provide an indication of the validity of the model. Furthermore, preliminary simulations were also undertaken to examine the KERS under three common drive cycles; two urban and one highway. The fuel consumption savings afforded by the KERS in the urban drive cycles was found to be within 12 – 15%, and the highway drive cycle showed only a small reduction in fuel consumption (5%). This is expected since the KERS is specifically designed to provide the greatest benefits for urban and/or congested duty cycles. However, the present numerical models have several acknowledged limitations that will be addressed in the future.

4.1 Future work

As the KERS operational trials have yet to commence at the time of writing, there is a significant amount of future work planned, briefly outlined as follows:

- Acquisition of KERS operational telematics data.

In conjunction with the current operational telematics data, once the KERS are operational the relevant telematics data for the system will be simultaneously monitored. This data will not only be analysed, but also used to assist in the validation of the numerical models.

- Acquisition of high-resolution drive cycles.

As shown, the event-driven telematics data does not possess a suitable resolution for obtaining drive cycle data. To obtain high resolution drive cycle data, an OBD data logger has been purchased and preparations are currently being made with the fleet operators to obtain relevant drive cycle data using this system.

- Detailed vehicle modelling using ADVISOR to develop accurate vehicle models.

The most pertinent limitations of the numerical vehicle models are to first improve the accuracy of the various vehicle parameters including aerodynamic drag, rolling resistance, and the fuel efficiency maps. Also, as stated above, the event-driven telematics data lacks the resolution required to replicate the transient events where the vehicle (and KERS) will need to be accurately assessed and simulated. Finally, road grade and elevation data are not available for the drive cycle data but will be acquired in the future to further improve the simulation accuracy.

A broader analysis using the updated and calibrated models with the acquired data will match suitable operating conditions for regenerative braking energy systems with the most cost-effective KERS architectures.

- Detailed KERS optimisation.

The development of accurate numerical vehicle models will provide a useful tool to maximize the commercial viability of this technology. These models will be used with various optimisation algorithms to optimise not only the KERS, but also routes and driving styles for various applications to minimise fuel consumption, GHG emissions and system costs, helping to identify the most commercially feasible solution.

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