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Energy Efficiency of Autonomous Car Powertrain

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Abstract

This paper investigates the energy efficiency and emissions benefits possible with connected and autonomous vehicles (CAVs). Such benefits could be instrumental in decarbonising the transport sector. The impact of CAV technology on operation, usage and specification of vehicles for optimised energy efficiency is considered. Energy consumption reductions of 55% - 66% are identified for a fully autonomous road transport system versus the present. 46% is possible for a CAV on today's roads. Smoothing effects and reduced stoppage in the drive cycle achieve a 31% reduction in travel time if speed limits are not reduced. CAV powertrain optimised for different scenarios requires just 10 kW – 40 kW maximum power whilst the vehicle mass is reduced by up to 40% relative to current cars. Urban-optimised powertrain, with only 10 kW – 15 kW maximum power, allows energy consumption reductions of over 71%. UK energy consumption by cars could be 30% – 45% of current levels with a fully autonomous road transport system, depending on an energy efficiency versus travel time trade off. This could be reduced to just 26% if ride-sharing in urban areas achieves a doubling in average occupancy and travel times remain at today's levels. A comparison of IC engine and battery-electric powertrains optimised for a fully autonomous road transport system indicates the benefits of electric powertrain, with a primary energy requirement per unit distance of ⅓ of the equivalent IC engine CAV. Greenhouse gas emissions per unit distance for the battery-electric CAV are 55% of an IC engine CAV with current UK electricity emissions intensity, reducing to 13% at 2030 emissions target levels. Reduced drive cycle energy requirements (44% of current levels) allow greater range and improved economics of electric vehicles whilst reduced power variance allows smaller batteries for hybrids, similarly helping their case.

Introduction

Climate change is a major contemporary issue, with 10% of global greenhouse gas emissions coming from road transport, the largest single contributor [1]. In the UK 78% of road transport mileage is by cars, showing them to be the major contributor to climate change of any transport mode [2]. The inefficiency of road transport extends beyond emissions, with extensive time wasted through congestion (45 seconds per vehicle mile on UK A roads [2]) and low capacity utilisation (1.52 average passengers per UK vehicle [3]) whilst consuming large amounts of space and money. With consumers constantly demanding 'quicker, cheaper and easier' in all facets of life whilst UK government targets have committed to major emissions reductions (80% by 2050 vs 1990 [4]), major changes to address the efficiency of the road transport system are required.

Connected and autonomous vehicles (CAVs) are set to revolutionise transport, transforming the way we interact with mobility whilst bringing benefits to energy efficiency and emissions, travel times, congestion and social integration. The impact of CAV technology on the vehicle and powertrain specification is potentially extensive, driven by increased efficiency of drive cycles and different usage patterns, hence is likely to be a major focus of development in the future. All energy efficiency benefits are realised through the powertrain, although it has been the subject of little research.

Energy efficiency of road transport can be improved through both the way we use the vehicles and the vehicle's technology. Changes to the vehicle's drive cycle and specification facilitated by connected and autonomous control of vehicles allow more efficient operation of each individual vehicle and the wider road transport system.

This project investigates the energy efficiency benefits possible with CAVs and how this will affect the powertrain requirements.

In this project, drive cycle simulations of vehicles over several connected, autonomous and conventional scenarios are compared to quantify energy efficiency benefits and understand the key variables and trade-offs. This analysis is based around conventional powertrain architecture (petrol IC engine). The energy and power requirements of the powertrain are largely independent of architecture, hence investigations of the vehicle (passive system) and service efficiencies are valid for any CAV architecture.

With battery range concerns in electric vehicles, IC engines dominate the road vehicle powertrain market, therefore any significant adoption of CAVs is likely to involve this powertrain architecture in the short term. CAVs could have a vast impact on this well-established industry if the powertrain requirements differ significantly.

Literature Review

The subject of CAVs is wide, complex and multidisciplinary, with research ranging from control logic [5] and traffic flow optimisation [6], to commercial models [7], travel sickness [8] and public acceptance [9] [10]. This study will focus on the powertrain and usage aspects important for energy efficiency of a CAV as part of the road transport system.

Previous literature reviews on the whole subject of autonomous driving show large increases in the number of publications over recent years [11]. This corresponds with increased industry and media interest, with CAVs approaching the peak of the 'hype-cycle', the precursor to the technology adoption cycle [12]. Significant publicity for Google's self-driving car and the U.S. DARPA Challenges have instigated this trend, with DARPA-related publications the most cited on autonomous driving in the 2000s [11]. More recently, the involvement of major car manufacturers, such as BMW, Ford and Volvo [13], along with ride-sharing services like Uber has re-energised the topic [14].

Despite the media focus on legal and commercial issues, technical research dominates with over 90% of CAV-related papers to 2015 [11], most of which are control focussed.

Media and industrial publications postulate wide ranging benefits for CAVs, including 90% safety improvements [15] and reductions in parking infrastructure [16], although little research has quantified these. The U.S. National Renewable Energy Laboratory (NREL) has produced significant research on CAVs, quantifying the energy efficiency benefits through a Kaya Identity approach, reporting the overall benefits of -173% to +95% [17]. Another study found 100% – 1000% fuel economy improvements [18], highlighting the strong dependency on assumed adoption scenarios.

Road transport system benefits are expected due to reduced vehicle numbers, with 42.6% – 66% reductions under a shared use model [19] [20]. However, an expected rise in the total number of vehicle miles travelled, of 9% – 90% [19] [17] [21] due to ease and wider access of travel, may partly offset this, an example of the rebound effect.

Of the CAV effects giving energy efficiency benefits (see Figure 5), those reducing vehicle weight and increasing drive cycle efficiency are seen to have greatest benefit. 75% weight reduction is reported possible, due to lower power requirements of smoother drive cycles enabling powertrain downsizing and reduced safety structures, with potential for 50% less energy-intense drive cycles, through smoothing and traffic optimisation [17]. Typical approaches used to assess usage-based benefits (those affecting the drive cycle characteristics but not the vehicle specification) are the modelling of traffic flows through agent-based simulation [22], or real-world testing through assessing changes in driving style [23]. However, these tend to be narrow in scope, with no simultaneous optimisation of all energy efficiency benefits conducted to date. The dependence of benefits on the scenario, characterised by the degree of autonomy, degree of CAV penetration, vehicle type, route and traffic mean that the combination of separate studies, scenarios and effects to find the overall impact is inaccurate, requiring a more holistic approach.

Studies quantifying the fuel efficiency benefit from efficient driving (reduced acceleration rate, reduced cruising speed, reduced start-stop where possible) report that 20% – 30% benefits are possible on current roads [23] [24]. The NREL study reported a 40% total when this was combined with further start-stop reduction due to collaborative CAV behaviour, with 100% penetration facilitated by connected technologies, represented by efficient traffic flow [17].

Traffic models for CAVs have been the frequent subject of research, with early models representing only their reactive autonomous behaviour in the absence of connected optimisation [25]. More recent work has incorporated the connected benefits of efficient traffic flow, with mathematical acceleration models enabling simulation and optimisation of traffic flow, reporting 50% throughput increases for 100% CAV penetration (vs 0%) [6]. A study of a four-way junction reports 15 % energy consumption reduction through employing a CAV control strategy [26]. Other studies employ agent-based modelling of connected vehicles (with both vehicle to vehicle and vehicle to infrastructure communications) to consider improvements of traffic speeds and homogenisation for improved flow. Whilst such studies show a benefit, they tend to focus on control strategies and optimisation algorithms rather than the associated energy benefits [27].

Under shared-use transport models, which many synonymise with CAVs, durability and range considerations may dominate powertrain configuration, with vehicles required to operate all day every day resulting in higher vehicle utilisation and longer mileage lifetimes than current cars [28]. This may rule out battery-electric vehicles which have limited range due to the low energy density of batteries and long recharge times.

Other more detailed studies relevant to CAVs include CFD analysis of platooning for HGVs, reporting 15% fuel consumption benefits for 2 m following distances [29].

As well as reducing the number of vehicles on roads, shared use transport systems could bring service efficiency benefits through improved vehicle utilisation. Reduced traffic would allow more efficient drive cycles through reduced congestion whilst simultaneously reducing travel times. The major barrier is a lack of public willingness to shift from a private ownership commercial model. Cars are currently seen as more than just a mode of transport, providing a space for storage, for meetings and personal expression [30]. This is supported by a study reporting ¾ of those interested in CAVs would pursue private ownership with only ¼ open to shared use fleets [10].

A study investigating efficient routing measured 1 to 3% energy consumption reductions with negligible change in journey time [31]. Results are highly dependent on geography and traffic, although they demonstrate a potential in also helping to alleviate congestion.

Work has focussed on usage optimisation of the vehicle, with powertrain considerations omitted in research [32] and industry alike. Most CAV activity employs battery-electric powertrain [28]; industry examples of this include Google and Tesla [13]. Consideration of extra-urban and inter-city travel would likely yield different powertrain decisions due to range restrictions of the current BEV powertrain.

The NREL study has identified the requirement for holistic simulation of both traffic systems to better understand CAV drive cycles (DCs), and of vehicles over these drive cycles to optimise powertrain specification and energy efficiency benefits [33]. No further progress has been published to date. However, companies including Bosch are working on holistic CAV DC simulations [28], indicating the growing interest of the automotive powertrain industry and growing demand for this train of research.

Overview

The objective is to compare the energy efficiency of CAVs with conventional vehicles. To achieve this, the mechanisms which reduce energy consumption must first be understood. A model to base comparative simulations on must also be established and validated.

This highlights the discrete modules of work forming the pathway to credible and relevant results.

Figure 1 shows the project structure, indicating the progression through work modules (numbered). Work is based around simulation of CAVs under different drive cycle scenarios (4), corresponding to different levels of CAV penetration in the road transport system from 0% – 100% CAVs. The baseline vehicle model for comparison is based on the average conventional vehicle of today (2).

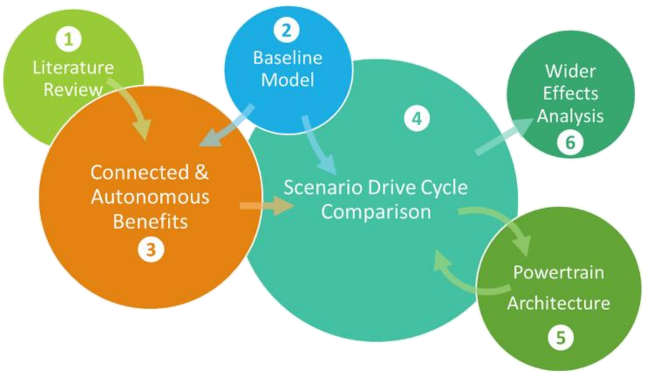

Figure 1. Paper overview with numbered work modules and arrows demonstrating work progression and information dependencies.

The powertrain specification is inherently linked with vehicle specification, both of which depend on the vehicle usage (drive cycle characteristics and usage intensity). Usage characteristics must be investigated and quantified before the powertrain and energy benefits can be optimised; in this investigation, the drive cycle characteristic usage factors are focussed on. Using sensitivity analysis of CAV benefit mechanisms (see 'CAV Benefits'), the major facilitators of energy consumption reduction and key affecting variables are established (3). This is used to inform how optimised CAV drive cycles differ from today's, enabling comparative simulations to be conducted over these drive cycles (4).

The base vehicle is modified for each scenario, optimising its specification for the given drive cycle and forming the basis of simulation and optimisation work (4). A comparison between scenarios highlights the optimal powertrain requirements and expected energy benefits through progression to a fully autonomous road transport system. Since the future scenarios through implementation of CAVs in practice cannot be predicted, bounding scenarios are considered to understand the major effects and the influence of key energy efficiency variables on the future road transport system.

The energy consumption reductions calculated in simulation can be extended to understand the implications to the whole road transport system (6). Powertrain architecture considerations (5) build off the identified powertrain requirements, considering the characteristics of different powertrain types and the limits to their optimisation. The overall energy efficiency of the mobility provided by CAVs can then be determined, combining powertrain, vehicle, usage and service energy efficiencies (see 'Method – Energy Efficiencies').

Method

Simulation

Physics based ADVISOR (Advanced Vehicle Simulator) software is used for modelling the vehicles and simulating drive cycles used throughout the project. The simulation starts from the drive cycle input (speed-time vectors), working through the physical energy chain from road load to powertrain operating point, to finally give energy and emissions outputs. The software is Simulink based, allowing operation through MATLAB for more complex simulations, optimisation and modification of simulation blocks. These blocks, shown in Figure 2, are written as individual MATLAB files allowing easy modification of the vehicle, powertrain or test cycle.

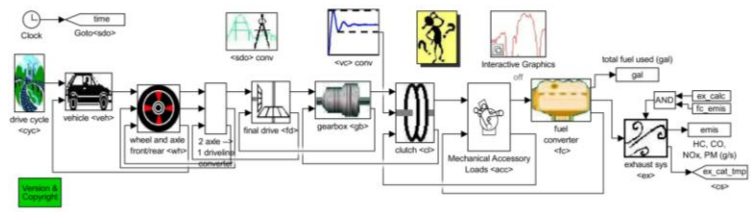

Figure 2. ADVISOR software block diagram showing the structure of the vehicle model and flow of information through the simulation. This diagram is for a vehicle with IC engine powertrain however blocks can be added or replaced for other powertrain architectures **[34]**.

Test data for the baseline vehicle and baseline scenario drive cycle (see 'CAV Scenario Simulation') was provided by MAHLE Powertrain Ltd., allowing validation of the baseline model and grounding all simulations in real-world test data to ensure accuracy. Final results from CAV scenario simulations have are not validated here as it is beyond the scope of this simulation-based investigation.

Energy Efficiencies

When considering the energy consumption of the road transport, it is useful to break the overall energy consumption down into terms which can each be attributed to a particular sub-system or set of variables, typically each informing a closely linked set of design or implementation decisions. This is demonstrated in Equation 1, describing the primary energy consumption in terms of powertrain (conversion device), vehicle (passive system) and service efficiencies and demand for passenger mobility (service).

Equation 1. Transport energy expansion showing powertrain (conversion device) efficiency, vehicle (passive system) efficiency and service efficiency. The decomposition of overall energy efficiency (primary energy per unit service) into its contributing factors is analogous to the Kaya Identity approach to greenhouse gas emissions **[30] [35]**.

$$Primary\ Energy = \frac{Primary\ Energy}{Useful\ Energy} \times \frac{Useful\ Energy}{Vehicle\ Mileage} \times \ldots$$

$$\ldots \times \frac{Vehicle\ Mileage}{Passenger\ Mobility} \times Passenger\ Mobility$$

The powertrain (conversion device) efficiency describes the energy efficiency in converting primary energy (e.g. petrol) into useful energy (i.e. engine work). Vehicle passive system efficiency describes the energy dissipated by drag, friction, acceleration and gravitational potential per unit vehicle distance travelled. The passenger mobility (service) efficiency is characterised by the vehicle utilisation and occupancy, represented by the vehicle mileage per unit passenger mobility (transport service) delivered. CAVs have an impact on all terms, with the mechanisms reducing each considered in 'CAV Benefits'.

Baseline Model

Establishment of a baseline model is important to maintain consistency and accuracy, minimising control-variable change between simulation scenario comparisons. To ensure the relevance of this work to the real road transport system, the model must be validated, with the choice of baseline also key. This baseline model forms a platform to base all simulation-based investigations on throughout subsequent sections, utilising the flexibility of simulation functions to modify the vehicle and test cycle in each case.

A 2010 Volkswagen Golf mk.6 1.4 L petrol (58 kW) was chosen for the baseline model, as the average road vehicle based on current UK vehicle ownership data [36]. This allows greatest relevance and potential impact of energy efficiency results.

Initial Model

The vehicle model is based around the fuel-flow map, physical attributes and loss factors of the baseline vehicle. A set of ADVISOR input MATLAB files (see Figure 2) were created to represent these factors, forming a simulation representation of the baseline vehicle for use in subsequent simulations (vehicle model data was provided by MAHLE Powertrain Ltd.).

This initial model was simulated over the New European Drive Cycle (NEDC) and validated with vehicle dynamometer test data (NEDC test data was provided by MAHLE Powertrain Ltd.). The NEDC is currently the main legislative drive cycle upon which all new cars are tested to check that emissions regulations are met and to report representative fuel economy. As a standard, test data is widely available hence results more easily reproducible, minimising sources of error and maximising accuracy of the baseline model and subsequent simulation results.

Initial results showed simulated fuel consumption values close to test values (1% lower). However, a comparison of fuel flow traces indicated significant discrepancies during warm-up and in steady-state operation (see Figure 3). The simulated fuel flow was lower than the test fuel flow over the warm-up period, as shown in Figure 3a, and 8.5% higher over the working temperature portion (900 s onwards, as shown in Figure 3b).

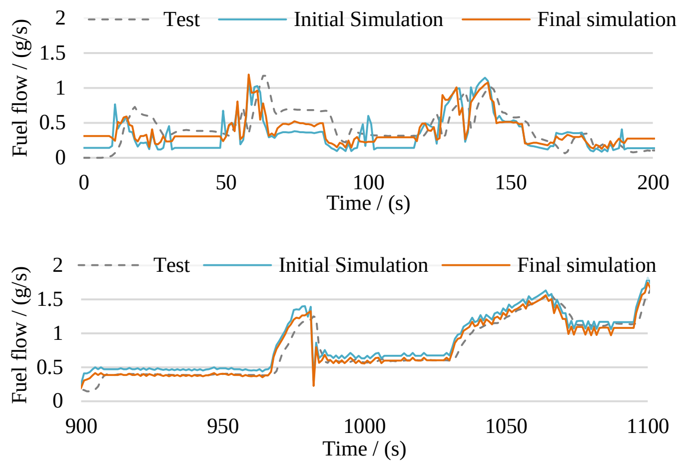

Figure 3. Test and simulation fuel flow traces over the NEDC. **(a) Cold-start (top):** Initial simulation underestimated the fuel flow during the initial warm-up period from cold-start, corrected in the final simulation. **(b) At working temperature (bottom):** Initial steady-state offset at working temperature was corrected in the final model.

Refinement

The offset of the two traces at working temperature, seen in Figure 3b, was deduced due to overestimated simulated system losses leading to an overestimation in engine torque requirements. A more refined set of gear efficiency maps were created, resulting in accurate matching of fuel flow rates at working temperature (see Figure 3b).

The underestimation of the simulated fuel flow during warm-up was found to be due to the lack of cold-start modelling. A cold fuel flow factor map (at 24 °C) was generated using the temperature difference between test data and initial simulation. Iteration of the cold fuel flow factor map scaling (i.e. scaling the gradient of blue line in Figure 4) allowed convergence of the full cycle fuel economy with test data.

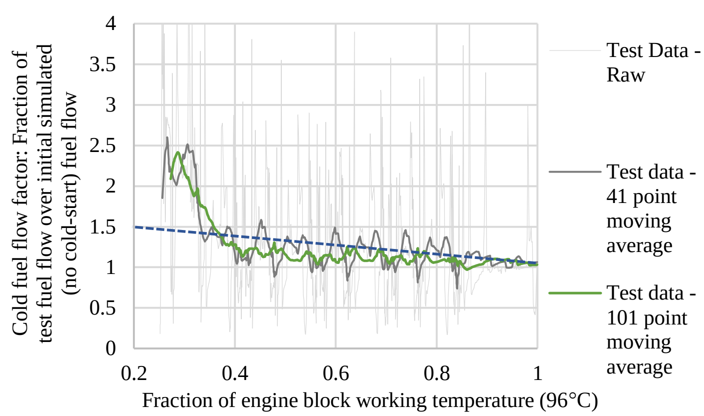

Figure 4. Cold fuel flow factor variation with temperature difference fraction below the working temperature. Note that it is also a function of engine speed and load, giving rise to the oscillations in test data with time. The blue line hence represents the average engine operating point's linear relationship between the two variables; there is a separate blue line for each engine operating point in practice, with the y-direction value at 24°C for each dictated by the cold fuel flow factor map.

The refined simulation fuel flow traces in Figure 3 show improved correlation with test data over the warm-up period. Due to the limitations of ADVISOR's linear cold-start function this was the best fit that could be obtained whilst maintaining an accurate overall NEDC fuel economy match.

CAV Benefits

Highlighted in the literature review, there exists a requirement for research providing accurate and holistic quantification of the energy efficiency benefits of CAVs, indicating the resulting changes in vehicle usage and specification.

Figure 5 shows the energy efficiency benefit mechanisms of a CAV road transport system. They are divided into system and vehicle levels, dependent on whether they are enabled by the technology of a single vehicle or a whole system of connected vehicles. The mechanisms are linked with the base variable (white clouds) through which they affect energy efficiency.

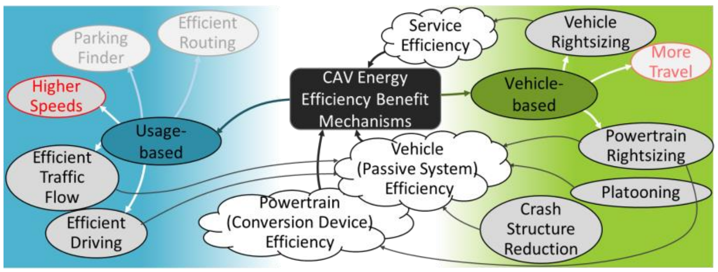

Figure 5. CAV energy efficiency benefit mechanisms (grey ovals) divided into usage-based and vehicle-based mechanisms dependent on whether they affect energy efficiency through changes to the drive cycle (usage) or changes to the vehicle specification. Benefits are linked with the energy efficiency term (white clouds) through which they directly affect overall energy efficiency (primary energy per unit passenger mobility service) (see 'Method – Energy Efficiencies'). Red mechanisms give negative benefit and faded mechanisms are not considered in this study.

Effects with the greatest potential energy efficiency benefit and those which could be effectively evaluated through simulation were focused on. Other mechanisms, except for higher speeds which is addressed, are independent of those considered here, and therefore their omission does not affect results.

Sensitivity analyses for each benefit mechanism were conducted, performing drive cycle simulations using the baseline model and NEDC as a basis for comparison. Only one variable was varied at a time, keeping all others constant (i.e. marginal allocation of fuel efficiency benefits). Whilst many of these variables have a nonlinear effect on fuel efficiency and each other, determining these interdependencies is beyond the scope of this project. The use of a typical vehicle and typical driving conditions ensures the relevance of sensitivity analysis results.

Efficient Driving

Efficient driving achieves a more efficient drive cycle enabled by autonomous, but not connected, control. This includes smoother acceleration and deceleration and stoppage avoidance where possible. Reduced cruising speeds have the potential for significant efficiency benefits, although there is a trade-off with travel time limiting this effect.

Efficient driving effects reduce the useful energy requirement of the drive cycle, increasing the vehicle (passive system) efficiency (see 'Method – Energy Efficiencies').

Sweeps

Sensitivity analyses of the key efficient driving variables were performed through sweeps of drive cycle acceleration rate (constant), cruising speed (constant) and distance. The drive cycle in each simulation consisted of a single acceleration – cruise – deceleration – idle pulse to the specified distance and constant time (i.e. trapezium speed-time profile).

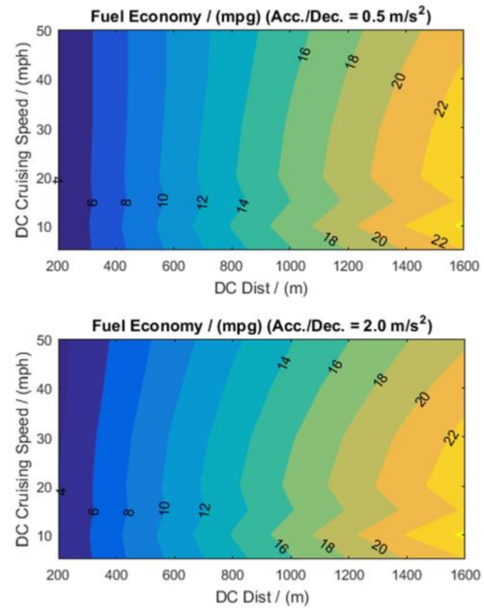

Figure 6. Fuel economy contour plots for single urban acceleration-cruise-brake-idle cycles over cycle distance and cruising speed sweeps. **(a)** 0.5 ms^{-2} acc./deceleration, **(b)** 2.0 ms^{-2} acc./deceleration.

Figure 6 shows fuel economy contour plots for these sweeps. The range of speeds and distances are representative of urban drive cycle segments between junctions, traffic lights or roundabouts. The acceleration rates are representative of the range observed in typical driving, supported by test data and studies [28].

The strong trend for higher fuel efficiency towards longer cycle distances in these urban cases is consistent with less stoppage per unit distance (stoppage density) being more efficient. Lower fuel efficiency is seen with increasing cruising speed for a given distance due to increased aerodynamic losses at higher speeds. This is only significant at longer distances where cruise makes up a larger portion of the cycle. Only minor differences in fuel efficiency (1.7 mpg max. at 50 mph, 1600 m) are seen for significant changes in acceleration rate (4-fold increase), highlighted in Figure 7.

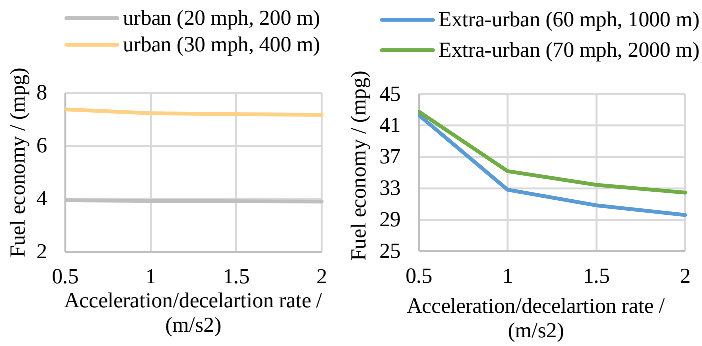

Figure 7. Relationship between fuel economy and acceleration/deceleration rate over representative urban **(a)** and extra-urban **(b)** drive cycle segments.

Comparison of graphs a and b in Figure 8, representing extra-urban drive cycle segments, show large changes in fuel efficiency with cruising speed for longer drive cycle distances.

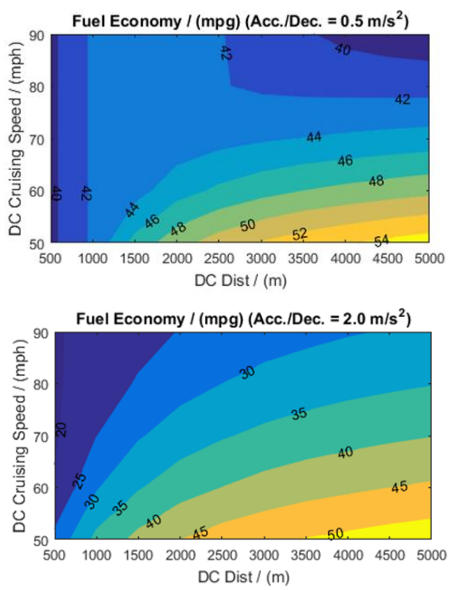

Figure 8. Fuel economy contour plots for single extra-urban acceleration-cruise-brake-idle cycles over cycle distance and cruising speed sweeps. **(a)** 0.5 ms^{-2} acc./deceleration, **(b)** 2.0 ms^{-2} acc./deceleration.

Acceleration rate is seen to have greatest effect for shorter cycles at higher speeds, representing larger proportions of the drive cycle under acceleration, demonstrated in Figure 7.

In both urban and extra-urban cases, the top left of the contour plot (high speeds and short distances) yields greatest benefit from acceleration rate reduction, with 13% and 50% maximum fuel consumption reduction between 2 ms^{-2} and 0.5 ms^{-2} for urban and extra-urban drive cycles respectively.

The dependence of fuel efficiency on acceleration rate and cruising speed over different distance and speed ranges is important in informing optimal CAV control strategy. The dominance of acceleration rate on fuel efficiency in urban conditions contrasted with the dominance of speed in extra-urban conditions could be particularly important in influencing the implementation of a CAV based road transport system.

Aggressiveness

Another approach to characterising the energy efficiency benefits of efficient driving is through comparison of drive cycles with differing driving style aggressiveness. Drive cycles representative of baseline and aggressive drive styles were taken from RDE test data. The baseline vehicle was simulated over these drive cycles, with the engine size scaled up to 91.9 kW to meet the maximum power condition of the aggressive cycle.

Results in Table 1 show reduced fuel economy for the aggressive case, confirming the positive impact of efficient driving, identified in sensitivity sweeps. Both average speed and average acceleration rate are lower despite this reduced energy efficiency. The peak acceleration and average power, however, are higher, consistent with a more aggressive driving style. The drive cycle proportion spent at motorway speeds, characterised by legislative RDE speed bands, is reduced despite the same route and a more aggressive driving style, suggesting that there was increased traffic in the aggressive case.

Table 1. RDE drive cycle aggressiveness comparison results. Both use the baseline vehicle model with powertrain resized to 91.9 kW (torque scaled with displacement).

Drive cycle characteristic		**Baseline**	**Aggressive**	**% Difference**
Total DC energy	MWh	31.1	33.5	7.7%
Average moving speed	m/s	14.5	14.0	-3.5%
Average acceleration	m/s^2	0.596	0.554	-6.9%
Peak acceleration	m/s^2	2.77	3.00	8.3%
Average power	kW	6.24	6.35	1.8%
Peak power	kW	53.4	66.2	24.1%
Peak torque	Nm	193.6	200.9	3.8%
RDE % stationary	% time of Urban	8%	7.8%	-2.5%
RDE % Urban	% total distance	42.6%	44.8%	5.2%
RDE % Rural	% total distance	23.1%	25.9%	12.1%
RDE % Motorway	% total distance	34.3%	29.2%	-14.9%

Histogram maps of the baseline and aggressive drive cycles are shown in Figure 9. Increased operation at high loads and speeds in the aggressive case, representing higher power, is characteristic of more aggressive driving. Increased operation at very low engine speed corroborates the increased traffic impact in the aggressive case.

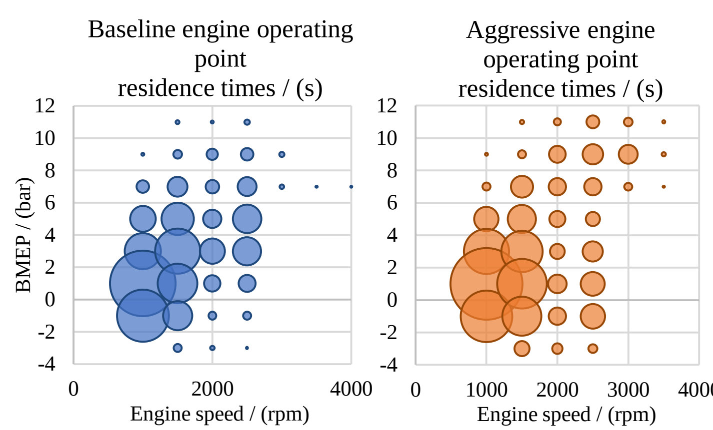

Figure 9. RDE test cycle aggressiveness comparison of engine operating point residence times **(a)** Baseline **(b)** Aggressive.

Vehicle Weight

The direct energy efficiency benefit of vehicle weight reduction is due to the reduced energy consumption during acceleration. The useful energy requirement over a drive cycle is reduced thus increasing the vehicle (passive system) efficiency (see 'Method – Energy Efficiencies'). An indirect energy efficiency benefit is seen through powertrain downsizing, allowed by the reduced vehicle weight and reduced drive cycle maximum power requirement, which improves powertrain (conversion device) efficiency.

The crash structure represents a sizeable fraction of the vehicle mass (typically 400kg [37]), required for safety in crashes, largely due to slow reaction times of human drivers. The extent of the crash structure reduction possible depends on the CAV penetration levels, which dictate the reduced crash risk due to faster responses of CAVs.

Powertrain rightsizing can have a significant effect on both vehicle weight and powertrain efficiency. It is, however, heavily dependent on the drive cycle and its maximum load point, and therefore on other benefit mechanisms. Any significant benefit through vehicle rightsizing requires a shared-use model of vehicle operation, with the increased occupancy of a vehicle equivalent to reducing the vehicle weight per passenger.

Figure 10 shows the possible fuel efficiency reductions by crash structure reduction and powertrain rightsizing of CAVs, highlighting high scenario and baseline dependence. Data points were generated through drive cycle simulation, varying the vehicle's chassis mass to model crash structure reduction and further lightweighting. Powertrain rightsizing was performed by iteration, as described later.

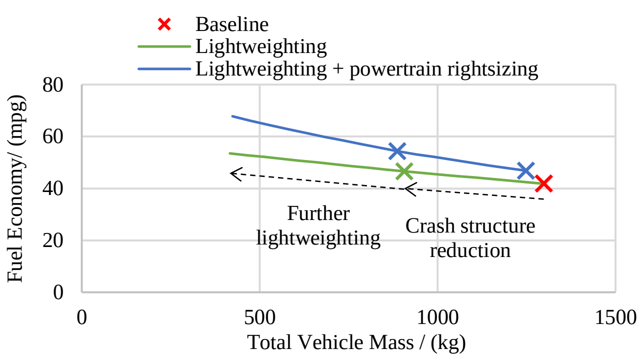

Figure 10. NEDC fuel economy benefit with vehicle weight reduction from crash structure reduction and powertrain rightsizing. Data points were generated through drive cycle simulation, varying the vehicle's chassis mass to model crash structure reduction and further lightweighting. Powertrain rightsizing was performed by iteration as described later.

The rightsized powertrain is only marginally larger than the baseline version, for baseline vehicle mass, yet yields an 11% fuel consumption reduction. Similar benefits are seen by eliminating the crash structure, with 11% fuel efficiency increase for the baseline case. Additional benefits are possible from further lightweighting, although the degree to which this is possible remains uncertain. The VW L1 concept demonstrated the potential for extreme lightweighting with a fuel economy of 240 mpg, but the cost of materials used and impact on comfort and usability limit its application in practice [38].

More significant fuel economy improvements were seen through vehicle rightsizing, with the effect equivalent to shared use of conventionally sized vehicles, increasing capacity utilisation, where the fuel consumption can be divided by the passengers.

Figure 11 demonstrates the benefit of increased vehicle utilisation, with a 218% increase in fuel economy per passenger possible for a fully utilised vehicle versus the current UK baseline of 1.52 people per vehicle [3]. Whilst vehicle rightsizing is possible with conventional vehicles, when combined with crash structure reduction and powertrain rightsizing the potential fuel efficiency benefit increases to 314%, demonstrating the benefit of its implementation with CAVs. They also offer alternative and more efficient operation formats for ride-sharing services, due to their automated and connected nature, which could improve market uptake, therefore facilitating vehicle rightsizing.

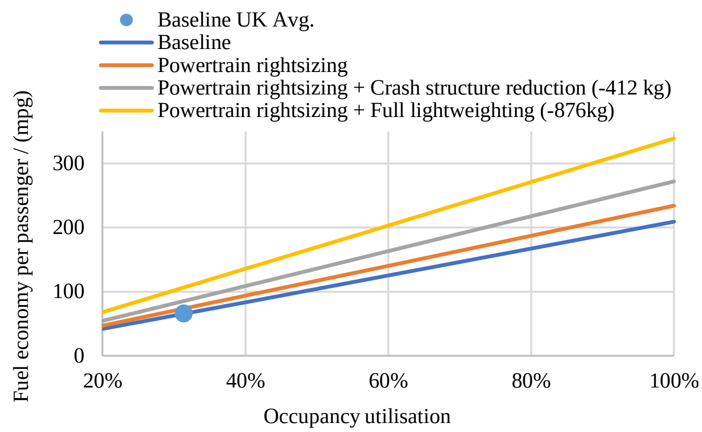

Figure 11. Effect of vehicle rightsizing on fuel economy per passenger. Data was generated from Figure 10 simulations, scaling the fuel economy by the occupancy relative to the UK standard, of 1.52 **[3]**, to give fuel consumption per passenger.

Platooning

Platooning is the collaborative behaviour of vehicles, following one another closely to reduce drag losses. With CAVs this can be exploited to great effect, facilitated by improved safety due to automated sensing and control, allowing reduced following distances between vehicles and therefore higher drag reductions. This reduces the useful energy requirement over a drive cycle thus increasing vehicle (passive system) energy efficiency (see 'Method – Energy Efficiencies').

The study of platooning and its effects on fuel efficiency are well documented. Accurate measures of its potential require detailed aerodynamic models, the results of which are applied over drive cycle simulation to understand the real-world benefit.

Taking an average drag reduction over different platoon chain lengths, vehicle number in the chain, following-distances and speeds, a representative value of 45% drag reduction from platooning was identified from aerodynamic model data of multi-vehicle platoons [39], supported by other studies [40].

Drag is proportional to the square of vehicle speed, hence a uniform reduction in drag coefficient over the whole drive cycle offers a good approximation of the effects of platooning.

The drag reduction was modelled by a reduction in the vehicle drag coefficient from the 0.32 baseline to 0.176. The results of simulation over the NEDC show platooning to produce a 7% increase in fuel efficiency, from 41 mpg – 44 mpg. The NEDC reflects a lower average speed than typical real-world driving, hence higher benefits are likely in practice.

Powertrain Rightsizing

Powertrain rightsizing means matching the powertrain's maximum power or torque output to the maximum load condition of the drive cycle concerned. In the case of IC engines, downsizing is well documented, allowing both weight savings and increased powertrain (conversion device) efficiency (see 'Method – Energy Efficiencies') due to reduced pumping losses. Conventional vehicles tend to have oversized engines to provide competitive transient performance, whereas CAVs no longer have this requirement. This allows more extreme downsizing and hence greater fuel efficiency benefits.

Figure 12 shows the engine operating point residence times of the baseline vehicle over the NEDC for standard and rightsized powertrains. The effect of downsizing has been modelled in the simulation by a simple scaling of the engine torque. This shrinks the engine map in the torque direction. In practice, this would be achieved through a reduction in engine displacement so the BMEP for a given torque demand would increase, thus increasing efficiency, as shown by the contours of BSFC in the figure.

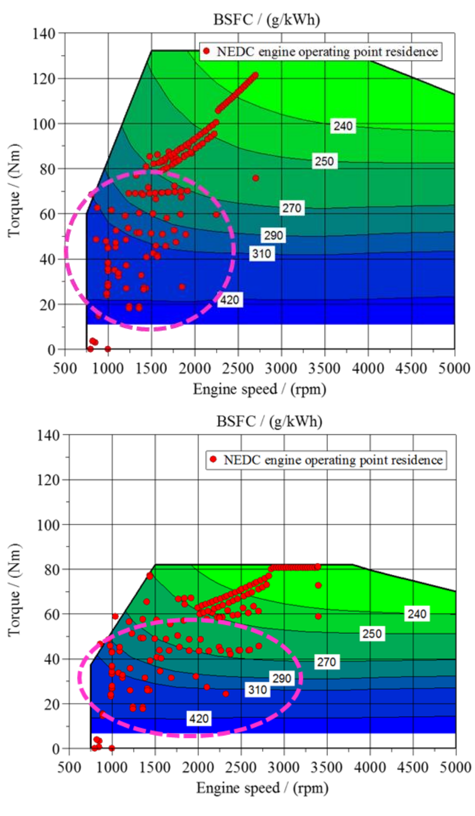

Figure 12. Effects of powertrain rightsizing (downsizing in this case) on operating points and therefore fuel efficiency, **(a)** Baseline, **(b)** Rightsized. Data points each represent 1 s of operation thus indicating the range and density of engine operating points over the drive cycle. The dotted circle shows the cruising regions of the drive cycle whilst higher strings of residence points represent accelerations.

In the baseline map (Figure 12a), there is an unutilised torque reserve at the drive cycle's maximum load point, indicating an oversized powertrain. In the rightsized case, the maximum engine *torque* is limiting, not maximum *power*, hence there is scope to reduce the gear ratios to use more of the engine speed range at maximum torque, allowing further downsizing. For typical IC engines, peak efficiency is at lower engine speeds (see Figure 23), due to increased frictional loading and thermal losses with engine speed. Therefore, such a gear strategy might reduce efficiency in practice.

Powertrain rightsizing requires iteration of the powertrain torque scale, as shown in Figure 13, because of the cyclic reduction between weight, due to downsizing, and required engine power, due to this reduced weight. A bisection method is used to converge on the rightsized torque scale. The lower convergence limit is set by a missed trace, indicated if the achieved vehicle speed deviates from that requested by more than 2 mph.

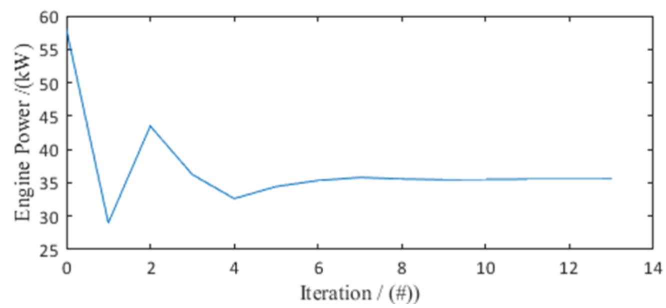

Figure 13. Powertrain torque scale iteration, converging on the limiting case of minimum powertrain size with no missed traces. The bisection method is used.

Fuel efficiency and powertrain specification results for the standard and rightsized powertrain are shown in Table 2. A 38% reduction in engine size provides a 19% reduction in fuel consumption over the NEDC. A CAV drive cycle may allow further downsizing due to the smoothing effects of efficient driving, hence reducing the maximum load condition.

Table 2. Powertrain rightsizing results over the NEDC.

Characteristic		Powertrain specification	
		Baseline	Rightsized
Fuel economy	mpg	41.0	50.6
Engine displacement	l	1.39	0.85
Max power	kW	58	36

Efficient Traffic Flow

Efficient traffic flow has a similar effect in smoothing the drive cycle to efficient driving. Whilst efficient driving uses the automated control technology of one CAV, efficient traffic flow utilises the connected nature of a system of CAVs to further reduce stoppage. This could eliminate congestion and traffic signals, whilst increasing the vehicle (passive system) efficiency (see 'Method – Energy Efficiencies') due to reduced useful energy consumption in acceleration.

A detailed analysis of efficient traffic flow effects and limits requires traffic simulation of the road transport system. However, bounding-case energy efficiency benefits can be gained using direct drive cycle manipulation within vehicle simulation, as done here.

The lower bounding case, with no efficient traffic flow, is the baseline simulation scenario from the main CAV scenario simulations (see later), representing a conventional vehicle on today's roads taken from RDE test data. A CAV drive cycle over the same RDE route is used as the upper bound, with 100% CAV penetration (see 'CAV Scenario Simulation'). The average acceleration rate and speed limits are the same in both cases, with the only differences being due to efficient traffic flow. The reduced stoppage achieved is shown in a comparison of the drive cycles in Figure 14.

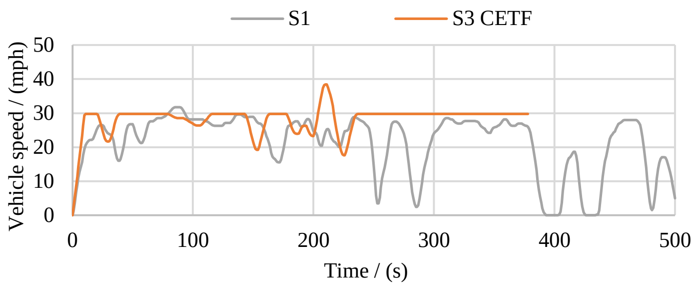

Figure 14. Drive cycle comparison between the baseline (RDE route, conventional vehicle on today's roads (S1)) and the same route with 100% CAVs employing efficient traffic flow (S3 CETF).

The energy efficiency benefit of efficient traffic flow is demonstrated in Table 3, with an 18.3% fuel economy increase over the RDE route. The effect on average speed of reduced stoppage results in a 47% reduction in travel time, representing the upper bound of travel time reduction possible from CAVs whilst maintaining today's speed limits. Greater reductions are possible with higher speed limits, enabled by improved vehicle safety, although would increase energy consumption disproportionately due to the squared relationship between drag energy losses and vehicle speed.

Table 3. Drive cycle simulation results between the baseline (S1) and efficient traffic flow drive cycles over the RDE route (S3 CETF).

Variable		Scenario		
		S1	**S3 CETF**	**% Difference**
Fuel economy	mpg	34.9	41.3	18.3%
Average speed	mph	29.8	43.8	47.0%

Benefit Mechanism Comparison

The relationships between CAV benefit mechanisms and their limiting variables are non-linear, making separation and allocation of the energy efficiency benefit provided by each difficult. Marginal allocation can be done by considering the change in fuel economy in applying each benefit mechanism independently to a consistent baseline drive cycle. This has been done with the baseline vehicle for the NEDC and the baseline drive cycle (S1), representing a conventional vehicle on today's roads, over the RDE route (see the next section), with results shown in Figure 15.

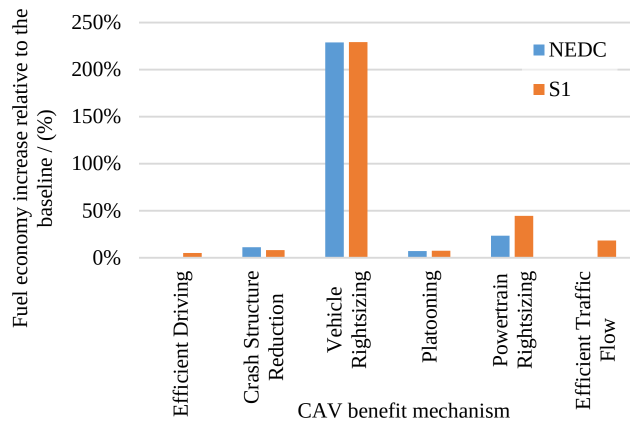

Figure 15. CAV energy efficiency benefits. Contributions shown from each benefit mechanism over the NEDC and baseline RDE drive cycles.

Vehicle rightsizing dominates energy efficiency benefits, but is heavily reliant on the shared-use operation of vehicles, with high social barriers to implementation. The fuel efficiency achieved by vehicle rightsizing in Figure 15 assumes 100% vehicle occupancy utilisation, representing the limiting case; actual benefits are likely to be much lower.

Of the other benefit mechanisms, powertrain rightsizing and efficient traffic flow achieve the greatest fuel efficiency increase. However, all mechanisms contribute significant energy efficiency benefits.

CAV Scenario Simulation

To determine the overall energy efficiency benefit of CAVs, the various benefit mechanisms must be considered simultaneously, combined under different scenarios dictating the validity and extent of each. These scenarios represent a set of assumptions describing the transport system in which the CAVs operate, with the level of CAV penetration (i.e. proportion of CAVs on the roads) a key variable. This was performed through simulation over a representative drive cycle along the same route for each scenario. The drive cycle and vehicle model used in each scenario reflects an integration of the benefit mechanisms in effect, through changes to drive cycle and vehicle variables, as discussed in the previous section. Comparison of results between scenarios allows an insight into how CAVs might affect the 3 factors of overall energy efficiency: powertrain (conversion device), vehicle (passive system) and service efficiencies (see 'Method – Energy Efficiencies'), as well as likely attributes of CAV drive cycles and vehicle specifications.

CAV Scenarios

The three scenarios considered in this investigation illustrate the path to an autonomous transport system. The bounding scenarios are the baseline vehicle under a conventional drive cycle typical of today's road transport system (S1 – baseline) and a fully connected and autonomous road transport system (S3 – fully autonomous). The intermediate scenario (S2 – isolated autonomous) represents an autonomous vehicle in isolation on today's roads. The structure of the simulations for these scenarios, their cases and sub-cases are shown in Figure 16.

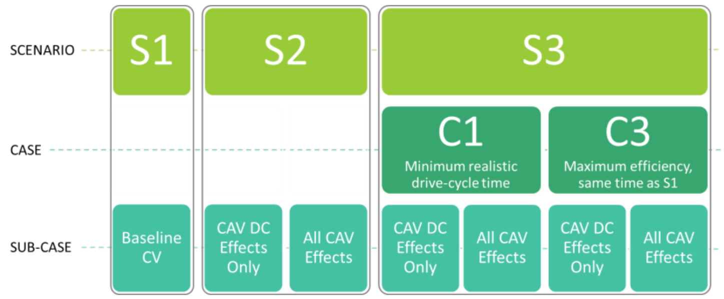

Figure 16. Simulation scenario and case breakdown.

The fully autonomous scenario allows employment of all CAV benefit mechanisms. Further energy efficiency benefits can be achieved through a reduction in speed limits, reducing the average speed and increasing travel time. This travel time versus energy efficiency trade-off depends on many factors including pressures for emissions reductions and the socio-economic implications of reduced travel times. It is not insightful to assume a position in this trade off when future decisions that will affect it are unknown; for this investigation, the bounding cases are considered. Case 1 of the fully autonomous scenario represents a maximum reduction in travel times, maintaining today's speed limits (S3 C1 – minimum time), whilst case 2 represents a maximum increase in energy efficiency, maintaining the same travel times as today (S3 C2 – maximum efficiency).

In each CAV scenario and case, separate simulation sub-cases are conducted to reflect vehicle usage-based benefit mechanisms only (UO), and all benefit mechanisms including both usage-based and vehicle-based benefit mechanisms (AE). Usage-based mechanisms alter the drive cycle but do not affect the vehicle's specification (e.g. efficient driving, efficient traffic flow) whereas vehicle-based mechanisms affect the vehicle's specification but have no effect on the drive cycle (e.g. powertrain rightsizing, platooning, crash structure reduction, vehicle rightsizing). This separation allows an indication of the energy efficiency benefits associated with powertrain (conversion device), vehicle (passive system) and service efficiencies.

Table 1 shows the CAV benefit mechanisms valid in each scenario, case and sub-case. Details of each mechanism can be found in 'CAV Benefits'. The impact of each mechanism in each scenario and case will differ as the extent to which each mechanism can be exploited (hence the benefit realised) depends on the other mechanisms employed and the wider system assumptions. This is discussed below through comparison of simulation results.

Table 4. CAV benefit mechanisms exploited in each scenario, case and sub-case. The upper section includes usage-based benefit mechanisms (those affecting the drive cycle), whilst the lower includes vehicle-based benefit mechanisms (those affecting the vehicle specification).

CAV benefit mechanism	Scenario / case						
	S1	S2		S3 C1		S3 C2	
		UO	AE	UO	AE	UO	AE
Efficient traffic flow				✓	✓	✓	✓
Efficient driving		✓	✓	✓	✓	✓	✓
Powertrain rightsizing			✓		✓		✓
Vehicle rightsizing			✓		✓		✓
Crash structure reduction					✓		✓
Platooning					✓		✓

Scenario modelling

Baseline scenario (S1)

The baseline scenario represents a conventional human-driven vehicle in today's road transport system. The drive cycle is taken from RDE test data, allowing greatest alignment with real driving and grounding the drive cycle in geographical data with known junction and traffic signal positions. The baseline vehicle is used for consistency with validation and benefit mechanism analysis. The powertrain is scaled to match the maximum power output of the vehicle used to record the RDE test data such that the drive cycle maximum load condition is met.

Fully autonomous scenario (S3)

With 100% CAV penetration in the fully autonomous scenario, the elimination of conventional vehicles allows centralised traffic flow scheduling to eliminate traffic signals. Low traffic and congestion levels indicated in the baseline scenario suggest that CAVs in equivalent conditions could eliminate congestion. These assumptions are incorporated into the representative drive cycle through removal of all traffic-based constraints. In heavy traffic conditions congestion could still be eliminated with redesign of junctions to allow increased flow of CAVs.

The drive cycle is generated from the RDE route but takes no cues from test vehicle data; it is only constrained by the distance-based speed restrictions imposed by speed limits and safe cornering speeds. A maximum acceleration rate is imposed by acceptable levels of comfort, characterised by the 'coffee cup test'; the maximum is set at 2 km/h/s, giving an average acceleration rate of 0.32 m/s^2 – 0.38 m/s^2 in accordance with studies [28].

An algorithm was written to aid drive cycle generation, also allowing modification of the key input parameters (speed limits, maximum acceleration rate). This algorithm takes the distance-based speed restriction vector as an input, dividing it into constant speed intervals. A trapezium speed profile is fitted to each interval, meeting the in-interval speed limit as well as start and end speed limits based on adjacent interval speed limits. The slope of trapezium start and end ramps are set at the maximum acceleration rate. This initial drive cycle fit for the minimum time case, hence using current speed limits, is shown as 'S3 C1 Linear' in Figure 17.

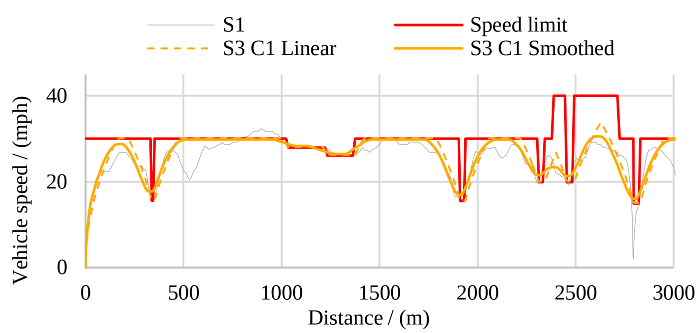

Figure 17. Scenario 3, case 1 drive cycle generation.

Acceleration is not linear in real driving, with smoothing into constant speed operation at its start and end, thus reducing average acceleration rates below the linear maximum imposed. This is provided by a smoothing function, with the resulting final drive cycle for the minimum time case of the fully autonomous scenario shown as 'S3 C1 Smoothed'.

The algorithmic drive cycle generation was repeated for the maximum efficiency case of the fully autonomous scenario (S3 C2), where speed restrictions were optimised to give the same travel time as the baseline scenario. A comparison between the resulting drive cycles are shown in Figure 18.

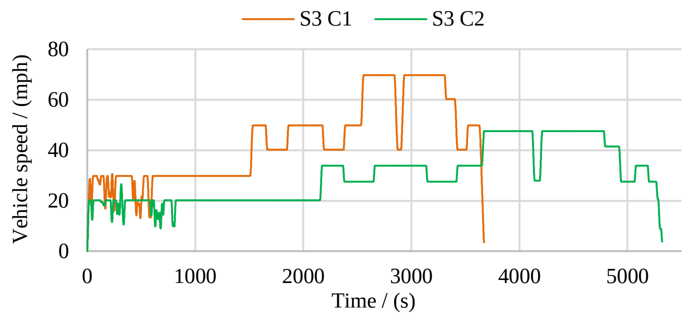

Figure 18. Fully autonomous scenario (S3), minimum time (C1) and maximum efficiency (C2) case comparison demonstrating the trade-off between average vehicle speed and time.

Energy efficiency benefits in the maximum efficiency case (C2) are increased relative to the minimum time case (C1) through the efficient driving mechanism, reducing average speeds. This can be achieved through reducing the acceleration rate and speed restrictions which characterise the drive cycles. A sweep of both acceleration rate and speed restrictions between C1 levels and realistic minima, set by traffic flow requirements, was conducted. A contour of speed scaling factor and acceleration scaling factor (versus the minimum time case) combinations achieving the same time as the baseline scenario was identified, along which the maximum fuel efficiency occurred at 0.70 speed scale and 0.36 acceleration scale. At acceleration rates below those used in the minimum time case, traffic flow issues emerge, particularly in merging flows of slow and fast-moving traffic or when integrating with conventional vehicles [41]. It was therefore decided to maintain a maximum acceleration rate of 2 km/h/s. A speed restriction scaling of 68% was identified. Additional to energy efficiency benefits, tyre wear and vehicle loading will be lower in this case and therefore durability and vehicle lifetime is likely to improve.

Isolated autonomous scenario (S2)

With the CAV in this scenario assumed isolated in a system of conventional vehicles, traffic signals and congestion constraints must be adhered to, as in the baseline scenario. The drive cycle modelling logic is to adhere to the equivalent fully autonomous drive cycle (S3 C1), unless the distance at a given time-step would exceed that of the baseline drive cycle (S1) in which case the speed is reduced (representing the same traffic constraints on the baseline vehicle in S1). In these deviations away from the fully autonomous drive cycle, the maximum acceleration rate must still be adhered to (see Figure 19).

This logic was used with a manual approach to generate a representative drive cycle. Only the urban section of the RDE route was modelled due to time constraints. The complex optimisation between competing drive cycle constraints proved time-consuming to automate. Therefore writing a generation function was beyond the limited time constraints of this project.

Scenario comparison

A comparison of the first 250 s of the scenario drive cycles is shown in Figure 19. The effects of traffic in the isolated autonomous scenario (S2 - blue line) compared with the minimum time case of the fully autonomous scenario (S3 C1 - orange line) can be seen in the figure. Sections where S2 exhibits a speed deficit represent the vehicle being held up by traffic. The reduced stoppage in the maximum efficiency case of the fully autonomous scenario allows lower cruising speeds compared with the baseline and isolated scenarios despite equal travel times. The effects of these drive cycle characteristic differences are discussed in the next section.

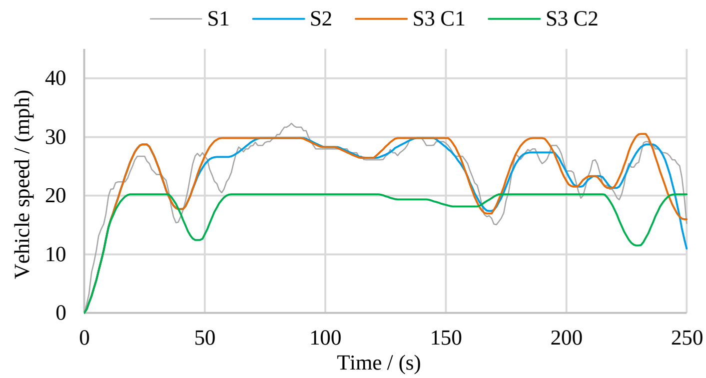

Figure 19. Simulation scenario drive cycle comparison. S1 is the baseline representing a conventional vehicle on today's roads, S2 represents a CAV in isolation on today's roads and S3 represents a CAV in a fully connected and automated road transport system. For S3, C1 is the maximum speed and minimum travel time case whilst C2 achieves the same travel time as the baseline scenario through reduced speeds.

The usage-based benefit mechanisms are incorporated into the simulation through the drive cycle as discussed above. The vehicle-based benefit mechanisms are implemented through modification of the baseline vehicle model, discussed below.

For both autonomous scenarios, powertrain rightsizing is implemented at a design condition, representing the highest load configuration of the scenario; occupancy is set as maximum with appropriate payload (+300 kg over baseline) and drag is kept at the baseline level (no platooning). For these autonomous scenarios the additional energy consumption by the additional CAV control systems required is neglected as modelling the changes in ancillary system energy consumption is beyond the scope of this high-level investigation focussed on powertrain. Furthermore, whilst current control systems (i.e. positioning sensors and communication hardware) consume a significant amount of energy in comparison with the vehicle's tractive energy requirements this is an area of intense development thus the control technologies used and their energy consumption are likely to differ significantly when CAVs are implemented to a significant degree in the transport system.

For the fully autonomous scenario the effects of crash structure reduction and platooning are implemented through changes to the vehicle's mass and drag coefficient respectively. A mass of 400 kg is subtracted, equal to a typical crash structure [37]. Recent super-efficient vehicle activity by Volkswagen indicates that anything beyond this is impractical, with the commercially-available XL1 weighing 795 kg despite the L1 concept demonstrating that 380 kg is theoretically achievable [42] [38]. A 45% drag coefficient reduction versus the baseline was used to model platooning as discussed previously. Vehicle rightsizing affects both the service efficiency, proportional to the number of passengers, and the weight of the vehicle, through a payload of 70 kg assigned to each passenger.

Under the usage-only sub-case of each scenario and case, the baseline vehicle is used unchanged over the relevant drive cycle. For the 'all effects' sub-case all relevant benefit mechanisms, shown in Figure 16, are implemented as described above.

Scenario simulation results

The major results from full drive cycle simulations of baseline and fully autonomous scenarios are shown in Table 5, with simulation cases and sub-cases as described above. The major results from urban drive cycle simulations for all scenarios are shown in Table 6.

Table 5. Simulation scenario, case and sub-case results for full drive cycles. The upper section of results relates to energy and efficiency, the middle to vehicle and powertrain specifications and the lower to drive cycle attributes. Scenarios, cases and sub-cases correspond to those described in 'CAV Scenarios'. 'UO' represents usage-based benefit mechanisms only, 'AE' represents all effects, both usage and vehicle-based mechanisms. All energy results are for a vehicle, not per passenger, hence do not include vehicle rightsizing benefits which are discussed separately.

Variable		**Scenario / case**				
		S1	**S3 C1**		**S3 C2**	
			UO	**AE**	**UO**	**AE**
Fuel economy	mpg	34.9	41.1	77.1	43.1	108.8
Brake Energy per km	kWh/km	0.133	0.120	0.074	0.090	0.058
Powertrain (conversion device) efficiency	%	18.5%	19.7%	22.8%	15.5%	25.1%
Vehicle (passive system) efficiency	kWh/km	0.717	0.610	0.325	0.582	0.230
Max power	kW	91.9	91.9	41.9	91.9	22.3
Mass	kg	1398	1398	852	1398	795
Cd	-	0.32	0.32	0.176	0.32	0.176
Avg. moving speed	mph	32.2	43.2		29.8	
Travel time	h	1.48	1.02		1.48	
Average acceleration/ deceleration rate	mph/s	1.382/-1.297	0.843/-0.891		0.727/-0.691	
Stoppage time fraction	%	7.25%	0.00%		0.00%	
Acc./Dec. time fraction	%	64.7%	13.9%		8.87%	

Table 6. Simulation scenario, case and sub-case results comparison for urban drive cycles. The upper section of results relates to energy and efficiency, the middle to vehicle and powertrain specifications and the lower to drive cycle attributes. Scenarios, cases and sub-cases correspond to those described in 'CAV Scenarios'. 'UO' represents usage-based benefit mechanisms only, 'AE' represents all effects, both usage and vehicle-based mechanisms. All energy results are for a vehicle, not per passenger, hence do not include vehicle rightsizing benefits which are discussed separately.

Variable		**Scenario / case**						
		S1	**S2**		**S3 C1**		**S3 C1**	
			UO	**AE**	**UO**	**AE**	**UO**	**AE**
Fuel economy	mpg	25.3	26.6	47.0	31.2	60.1	31.9	83.3
Brake Energy per km	kWh/km	0.12	0.11	0.10	0.09	0.06	0.09	0.06
Powertrain (conversion device) efficiency	%	12.0 %	11.3 %	18.6 %	11.4 %	14.9 %	10.8 %	19.6 %
Vehicle (passive system) efficiency	kWh/km	0.99	0.94	0.53	0.80	0.42	0.79	0.30
Max power	kW	91.9	91.9	37.1	91.9	41.9	91.9	22.3
Mass	kg	1398	1398	1239	1398	852	1398	795
Cd	-	0.32	0.32	0.32	0.32	0.176	0.32	0.176
Avg. moving speed	mph	19.4	17		27.1		18.7	
Travel time	min	17.2	17.2		11.2		15.5	
Average acceleration/deceleration rate	mph/s	1.51/ -1.38	0.844/- 0.869		0.855/- 0.830		0.737/- 0.693	
Stoppage time fraction	%	14.4 %	2.60%		0.00%		0.00%	
Acc./Dec. time fraction	%	67.8 %	67.7%		25.2%		25.2%	

For both full and urban drive cycles the fuel consumption reduction employing only usage-based benefit mechanisms is small but significant (26% – 20%). Higher benefits are shown when employing both usage (those affecting the drive cycle characteristics) and vehicle-based (those affecting the vehicle specification) benefit mechanisms, with over 67% fuel consumption reductions seen in the maximum efficiency, fully autonomous case (S3 C2) over both full and urban cycles. The benefit of usage-based effects is small compared with all effects (AE). However, the major vehicle-based mechanism, powertrain rightsizing, is heavily dependent on drive cycle smoothing, due to efficient traffic flow and efficient driving usage-based mechanisms, illustrating the allocation problem of benefits. Significant benefits are also achieved in the minimum time, fully autonomous case (S3 C1) (55% – 58%) despite a simultaneous reduction in travel times by 31%. The isolated autonomous scenario (S2) achieves an 46% fuel consumption reduction over the urban RDE section compared with the baseline scenario (S1). Note that these numbers represent the vehicle, and not passenger, fuel economy and therefore exclude vehicle rightsizing benefits. Whilst this demonstrates the potential benefit of a connected system, in the difference between the fully and isolated autonomous scenarios, it also shows that significant energy efficiency increases are possible for a CAV on today's roads. Other scenarios indicate that the proportional fuel consumption reductions over full and urban drive cycles are similar and therefore reductions of 44 % can be expected for the isolated scenario over the full drive cycle.

The benefit of vehicle rightsizing can be calculated for all scenarios: the overall vehicle energy efficiency (comprising powertrain (conversion device) and vehicle (passive system) efficiencies) is multiplied by the service efficiency, which is proportional to the number of passengers in the vehicle, to give the overall transport efficiency (see 'Vehicle Weight'). With 100% occupancy utilisation, this gives an overall fuel consumption reduction of 76% for the isolated autonomous scenario (S2, urban only), 86% for the fully autonomous scenario, minimum time case (S3 C1) and 89% for the maximum efficiency case (S3 C2).

Drive cycle characteristics reflect the effects discussed in 'Scenario Modelling' with the average speeds and stoppage time fractions reflecting the reduced stoppage in autonomous scenarios due to efficient driving and efficient traffic flow. Travel time reductions of 31% are achieved in the fully autonomous, minimum time case. Reduced average acceleration and deceleration rates in autonomous scenarios reflect the effects of efficient driving in smoothing the drive cycle. Both differences are illustrated in Figure 19.

The effect of powertrain rightsizing is seen in the maximum power specifications for each scenario's powertrain. In the fully autonomous scenario, maximum efficiency case (S3 C2) the required engine power is just 24% of the baseline. At this scale, it becomes challenging to make efficient and durable engines.

The weight effects of crash structure reduction and powertrain rightsizing are demonstrated, with a 40% vehicle mass reduction possible for the fully autonomous cases (S3). The smaller reductions in the isolated scenario (S2) demonstrate the limitations imposed by conventional vehicles mixing with CAVs.

The reduced torque requirement and greatly reduced torque variability in the fully autonomous scenario (S3) relative to the baseline are illustrated in Figure 20. For the S3 cases, the limiting powertrain rightsizing condition is dictated by the peak torque requirements, occurring at the end of acceleration to the maximum cruising speed (70 mph). With the required torque peaks well below those of the baseline scenario, due to efficient driving, the potential for downsizing becomes evident.

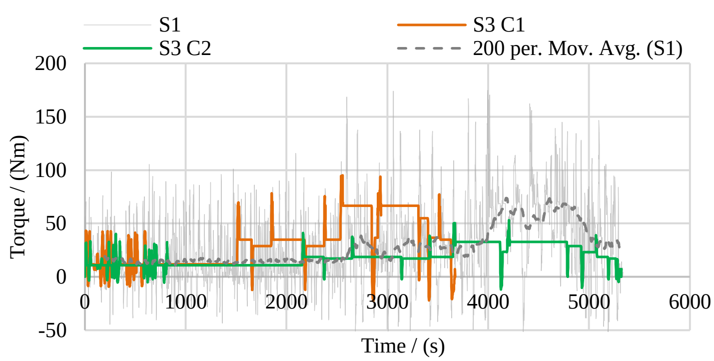

Figure 20. Torque-time comparison for full drive cycle scenarios. Autonomous scenarios (S3) can be seen to give lower torque variation and peaking.

The rate of change of torque is important in affecting non-CO_2 emissions, allowing better fuelling control and consequently reduced NO_x and PM emissions. Figure 21 shows the reduced spread in rate of change of torque over the autonomous drive cycles relative to the baseline. This reduction is due to smoother, less aggressive driving borne by the efficient driving benefit mechanism.

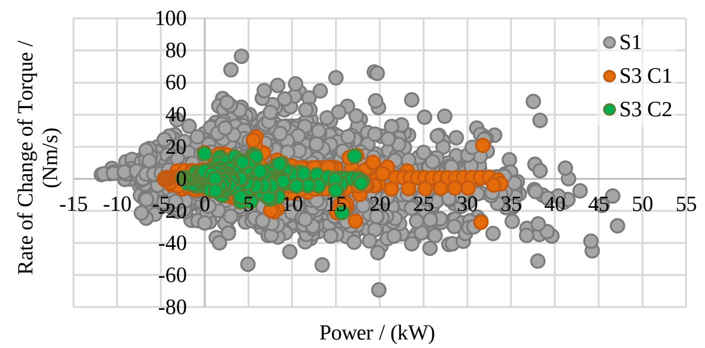

Figure 21. Rate-of-change-of-torque comparison for full drive cycle scenarios.

Figure 22 shows the comparison of energy efficiency benefits for the urban scenarios with both full cycle rightsized powertrain and powertrain rightsized for the urban section only ('urban optimised'). Urban optimised scenarios represent a vehicle only operating over urban drive cycles, hence has a reduced maximum cruising speed and therefore a reduced maximum torque requirement, allowing more aggressive downsizing. The difference in energy efficiency between the urban and urban optimised cases is due to this change in powertrain size alone, demonstrating the high benefits associated with this mechanism.

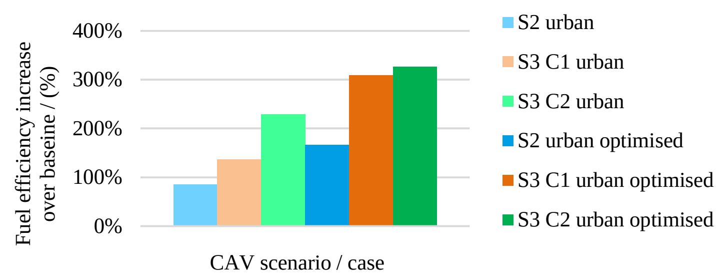

Figure 22. Fuel efficiency benefit from usage and vehicle-based benefit mechanisms (all effects, except vehicle rightsizing) for each scenario and case. The improvement is relative to the baseline vehicle's fuel efficiency over the relevant drive cycle. Urban simulations are rightsized at the full drive cycle design condition (see 'Scenario Modelling') whereas the urban optimised simulations are rightsized for the urban drive cycle only, hence a reduced power design condition.

The reductions in engine maximum power output and vehicle weight due to downsizing are shown in Table 7, highlighting an extreme departure from the current vehicle and engine specifications.

Table 7. Simulation scenario, case and sub-case results comparison for urban drive cycles with powertrain rightsized for the urban drive cycle in each (urban optimised).

Variable		**Scenario / case**			
		S1	**S2**	**S3 C1**	**S3 C2**
Fuel economy	mpg	25.3	67.4	103.6	108.1
Max. power	kW	91.9	15.0	11.7	11.7
Mass	kg	1398	1174	764	764

Powertrain Optimisation

IC Engine

The powertrain rightsizing conducted in scenario simulations maintains no torque reserve at the drive cycle's peak torque point, thus in practice less aggressive downsizing would be done, allowing a buffer. Another issue with operating at the maximum torque line is the low engine efficiency in that region for typical engine maps (see Figure 23a). Operation in this region is, however, only over short periods during acceleration, which is less frequent for CAV drive cycles. The efficiency benefits gained by the additional downsizing allowed by operating close to the torque limit are therefore likely to outweigh the penalty in efficiency during acceleration (see Figure 23b).

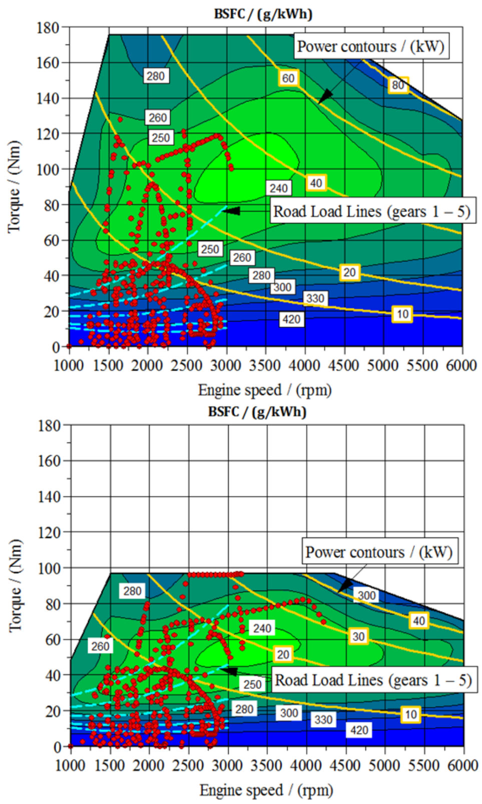

Figure 23. Engine operating point residence (red dots – each representing 1 s operation) maps over the fully autonomous, minimum time drive cycle (S3 C1) for **(a)** 80 kW (standard) and **(b)** 44 kW (rightsized) I3 engines. Powertrain optimisation is demonstrated using this engine and not the VW I4 as the BSFC contour shapes are more representative of typical IC engines.

Downsizing reduces the torque reserve in all gears, as indicated by comparison of the road load lines between the two maps. The gear ratios required are dictated by the range of operating speeds and therefore remain unchanged. In-gear acceleration will thus be limited by the reduced torque reserve. However, there is a reduced acceleration requirement for CAVs hence the required torque reserve is considered during powertrain rightsizing.

Other Architectures

Hybridisation of the powertrain would allow additional downsizing, offering further energy efficiency benefits. With an electric drive system to provide the torque reserve required for acceleration up to the maximum cruising speed (i.e. peak torque), the IC engine could be sized to provide the maximum torque required during cruise (see Figure 20) and therefore significantly smaller than the rightsized IC engines in the analysis above. The minimum time case of the fully autonomous scenario is likely to yield a greater benefit from this than the maximum efficiency case as higher cruising speeds give a greater torque difference between the end of acceleration and cruise.

The powertrain (conversion device) energy efficiency benefit yielded by additional downsizing is compounded by that of the electric drive system, typically achieving efficiencies of 80%. When averaged over both IC engine and electric drive energy demand, the overall powertrain efficiency would be much greater than an IC engine alone.

The major argument against battery electric vehicles in today's road transport system is the limited range provided by low energy density, heavy and expensive batteries. The fully autonomous scenario, maximum efficiency case lends itself to BEV architecture as average power demand is low, (50% of the baseline scenario) offering better range. Power variance is also low, so a series hybrid architecture would work be well-suited, allowing the battery that buffers the difference between engine and vehicle operating points to be small.

For the urban optimised powertrain, a hypothetical scenario could be a fleet of CAVs operated over urban areas only. The peak torque during acceleration is close to the peak torque during cruise thus hybrid architectures offer little benefit over IC engines alone. BEV powertrain is unsuitable as economic considerations give a high range requirement. IC engine, hybrid or hydrogen fuel cell powertrain would offer range benefits. However in the long term, fast-charging or battery change infrastructure could avoid this issue with BEVs. The infrastructure to achieve this or hydrogen fuel cell vehicles would require time and investment to implement, thus in the short-term IC engine or hybrid vehicles should prevail.

Wider Effects

The overall impact of CAVs on the road transport system depends on their commercial and operational implementation. For example, if private ownership still dominates then ride-sharing and therefore vehicle rightsizing benefits will be limited. Operationally, system energy efficiency is affected by whether one CAV covers the range of driving conditions and journey lengths of conventional vehicles, or whether CAV designs are more targeted for particular drive cycles (e.g. urban, extra-urban). Here, different implementations are considered to gauge the overall reduction in energy consumption, and therefore CO_2 emissions, possible in a fully autonomous road transport system.

If private ownership remains standard and vehicles still cover the multitude of operations as they do today, the overall energy consumption by cars in the road transport system will reduce as per the fully autonomous (S3) simulations. From Table 5 this would result in 32% – 45% of today's energy consumption by cars, bounded by the travel-time versus efficiency trade-off, with the lower limit corresponding to the same travel times as today but lower speed limits (S3 C2), and the upper corresponding to a minimum travel time within today's speed limits (S3 C1).

If CAVs are optimised to operate over only urban or extra-urban drive cycles, there is further potential for reduced energy consumption, due to additional powertrain downsizing, as demonstrated by the urban optimised cases in 'CAV Scenario Simulation'. In this case, 31% – 39% of today's energy consumption by cars would be achieved, under the same bounding scenarios. Furthermore, if these urban-only CAVs were operated under a ride-sharing scheme, allowing, for example, a doubling of the average urban occupancy, the overall energy consumption by cars could be 26% – 35% of today's.

These calculations consider only the cars present in the road transport system. Whilst they do account for 63% of road vehicle energy usage [43], there is potential for energy consumption reductions in other vehicles.

The total mileage by cars is assumed constant, although there is likely to be an increase due to the rebound effect of faster and cheaper travel. This would partly reduce the energy consumption reduction achieved by CAVs.

Energy consumption reduction figures use results for IC engine powertrain. There are additional energy efficiency benefits possible by switching to other powertrain architectures, due to higher powertrain efficiencies. A mix of powertrain architectures is likely due to a spread in required vehicle range and driving characteristics. This will act to reduce the overall energy consumption of CAVs.

Powertrain Architecture

Simulations of CAV scenarios have focussed on the changes in vehicle (passive system) efficiency, service efficiency and IC engine powertrain (conversion device) efficiency. To complete the picture of CAV impact on overall energy efficiency and emissions, the powertrain efficiency of alternative powertrain architectures and carbon intensity of the primary energy source must be considered. This is done through comparing results from optimised specifications of different powertrain architectures under the minimum time, fully autonomous scenario (S3 C1), representing a fully autonomous and connected car transport system with today's speed limits. For the battery-electric powertrain, the battery capacity is specified to allow 2 hours of range over the drive cycle route at the design condition (representing the highest load configuration of the vehicle). Data suggests that people are willing to travel for up to 2 hours per day [30]; this value therefore gives reasonable battery capacity and corresponding vehicle mass values for the purpose of energy and emissions estimations.

The major simulation results are shown in Table 8. The battery electric vehicle (BEV) requires more useful energy per unit distance than the IC engine vehicle because of its higher mass due to the batteries, indicated by the vehicle (passive system) efficiency. This results in higher power requirements, however the motor itself can have a smaller maximum power output (20.2 kW) than the IC engine (41.9 kW) over the same drive cycle due to its operational characteristics.

Table 8. Simulation results for an optimised powertrain architecture comparison for the fully autonomous minimum time scenario (S3 C1) over the full RDE drive cycle route. BEV represents battery electric vehicle powertrain architecture. Greenhouse gas (GHG) intensity values are official 2016 UK government values [44] .

Variable		**Powertrain architecture**	
		IC	**BEV**
Powertrain efficiency	%	22.8%	83.5%
Vehicle efficiency	kWh/km	0.074	0.089
Primary energy GHG intensity	gCO_2e/kWh	245.5	412.1
Primary energy per unit distance	kWh/km	0.325	0.107
GHG emissions per unit distance	gCO_2e/kWh	79.71	43.89
Powertrain max. power	kW	41.9	20.2
Battery capacity	kWh	-	21.4
Vehicle mass	kg	852	1439

The gear ratios and gear shift profiles of an IC engine powertrain favour operation at low engine speeds and high loads to give higher efficiencies. This means that the engine is torque-limited and therefore requires an over-specified maximum power output. Electric motors, however, can use their full speed range, allowing their maximum power output to be specified closer to the maximum power demand. Furthermore, the motor in this case has an over-torque rating of 1.8, allowing operation at 180% of maximum rated power output for short periods of time. These factors allow a motor with less than half the rated power of the equivalent engine to be used.

The higher efficiency of electric motors than IC engines is demonstrated with a powertrain (conversion device) efficiency almost 4 times greater. Combining powertrain and vehicle efficiencies gives a primary energy requirement per unit distance for the electric vehicle 3 times lower than the IC engine vehicle. This result can be extended to find the greenhouse gas (GHG) emissions per unit distance for each architecture, using appropriate GHG intensity factors for the primary energy vectors: petrol and UK electricity [44]. With the current UK electricity generation mix, electric CAV emissions are almost half those of the IC engine CAV over the same drive cycle. This will only improve as the electricity grid is decarbonised in line with carbon budgets [4]. 100 gCO_2e/kWh GHG intensity of UK electricity, regarded as what is required by 2030 to meet decarbonisation targets, would result in electric CAV emissions of only 13% of the equivalent IC engine vehicle.

Whilst the superior energy and emissions performance of electric powertrain architecture for CAVs is demonstrated, range remains a major issue. Typical car journey distances are well below the range of typical electric vehicles [2]. However, range anxiety limits their uptake in the market. Both behavioural change in vehicle use and more comprehensive electric vehicle charging infrastructure are required to overcome this. The improved range of electric CAVs, due to reduced primary energy consumption per unit distance, might incentivise these changes.

Conclusions

High energy and emissions reductions are possible through the use of connected and autonomous vehicles (CAVs) in the road transport system. The extent of these reductions depends on the many implementation decisions and other elements of the transport system limiting the space for optimisation and position of the travel time versus energy efficiency trade-off. Overall vehicle energy efficiency (combining the powertrain (conversion device) and vehicle (passive system) efficiencies) increases of over 200% (equivalent to energy consumption reductions of 67%) versus current typical driving are possible in a fully connected and autonomous road transport system. Autonomous vehicles in isolation on today's roads could achieve 86% overall vehicle energy efficiency increases (46% energy consumption reduction).

The direct energy consumption reduction due to CAV effects on the drive cycle (usage-based: efficient driving and efficient traffic flow) are relatively small, at 16% – 20%, depending on the scenario. The benefit due to effects on vehicle specifications (vehicle-based: powertrain rightsizing, crash structure reduction and platooning) is larger, but partly dependant on the drive cycle smoothing achieved by usage-based mechanisms, making allocation of the benefit difficult. The usage-based CAV benefit mechanisms lead to a smoother drive cycle, offering significantly reduced stoppage and potential congestion elimination with 100% CAV penetration. There is potential to increase benefits by reducing cruising speeds in a fully autonomous road transport system, but this is constrained by a travel time versus energy efficiency trade-off. The major vehicle-based effect is powertrain downsizing, achieving 23 to 45% energy consumption reductions dependent on the baseline and drive cycle, whilst weight reduction and platooning also offer significant benefits with high CAV penetration. Shared-use operation of CAVs offers the greatest energy consumption reduction per passenger of any benefit mechanism, with an reduction of 89% possible in a fully autonomous RTS, however is reliant on ridesharing commercial models which have significant social barriers.

Hybridisation and electrification can increase powertrain energy efficiency, with a stronger case for both in CAVs due to the reduced average power demand and power variance, therefore improving range and allowing smaller batteries. Given that the latter are major barriers to EV adoption, better economics may make EV architecture more competitive in CAVs. Optimised battery-electric powertrain for a CAV in a fully autonomous transport system requires just ⅓ of the primary energy of an equivalent IC engine vehicle. Greenhouse gas emissions of the electric CAV would be 55% of those of the petrol CAV at current UK electricity emissions intensity levels, reducing to 13% in 2030 if the electricity grid is decarbonised in line with targets.

Recommendations

This investigation has calculated the range of potential energy efficiency benefits in implementing CAVs into the road transport system and identified and characterised the mechanisms through which they may be achieved, based on a set of scenarios. The extent to which these benefits are achievable depend on limits set by the implementation pathway of CAVs and the surrounding transport system. There is scope to investigate these limits to better understand likely energy efficiency levels under implementation pathway scenarios. This would be invaluable to those making implementation decisions.

Electrification and hybridisation strategy optimisation for CAV drive cycles is one area where more detailed investigations would be valuable. These architectures appear to suit CAV drive cycle requirements, and a better understanding of the range versus energy efficiency trade-off is required for a balanced powertrain architecture comparison.

Agent-based traffic simulation of CAV transport systems would offer a better connection between CAV usage-based benefit mechanisms, implemented through control strategies, and drive cycle simulations. This presents a good opportunity for more detailed investigations into CAV drive cycles and their optimisation under energy efficiency, travel time and traffic flow objectives, in turn informing more accurate CAV drive cycle simulation and their optimisation.

References

1. T. Herzog and J. Pershing, "Navigating the Numbers: Greenhouse Gas Data and International Climate Policy," World Resources Institute, Washington, D.C., 2005.
2. D. Anderson, "Transport Statistics: Great Britain 2016," Department for Transport, London, 2016.
3. National Travel Survey, *Table NTS0905 - Car occupancy, England since: 2002,* London: Department for Transport, 2016.
4. Comitee on Climate Change Contributors, "Carbon Budgets and targets," The Comitee on Climate Change, [Online]. Available: http://bit.ly/1V2UBq7. [Accessed 13 January 2017].
5. A. Stotsky, C. Chien and P. Ioannou, "Robust Platoon-Stable Controller Design for Autonomous Intelligent Vehicles," *Mathematical and Computer Modelling,* vol. 22, no. 4-7, pp. 287-303, 1995.
6. A. Talebpour and H. Mahmassani, "Influence of connected and autonomous vehicles on traffic flow stability and throughput," *Transportation Research Part C,* vol. 71, pp. 143-163, 2016.
7. J. Yun, D. Won, E. Jeong, K. Park, K. Yang, J. Yang and J. Park, "The relationship between technology, business model, and market in autonomous car and intelligent robot industries," *Technological Forecasting & Social Change,* vol. 103, pp. 142-155, 2016.
8. C. Diels and J. Bos, "Self-driving carsickness," *Applied Ergonomics,* vol. 53, pp. 374-382, 2016.
9. M. Kyriakidis, R. Happee and J. de Winter, "Public opinion on automated driving: Results of an international questionaire among 5000 respondants," *Transportation Research Part F,* vol. 32, pp. 127-140, 2015.
10. J. Piao, M. McDonald, N. Hounsell, M. Graindorge, T. Graindorge and N. Malhene, "Public views towards implementation of autonomated vehicles in urban areas," *Transportation Research Procedia,* vol. 14, pp. 2168-2177, 2016.
11. J. Rosenzweig and M. Bartl, "A Review and Analysis of Literature on Autonomous Driving," *The Making-of Innovation E-Journal,* 9 October 2015.
12. M. Bartl, "The Future of Autoomous Driving - Intoducing the Foresight Matrix to Support Strategic Planning," The Making-of Innovation, 17 April 2015. [Online]. Available: http://bit.ly/2jHO1cO. [Accessed 12 January 2017].
13. CB insights, "33 Corporations Working On Autonomous Vehicles," 2016. [Online]. Available: http://bit.ly/1GmTYfX. [Accessed 5 December 2016].

14. Volvo contributors, “Volvo Cars and Uber join forces to develop autonomous driving cars,” Volvo, 18 August 2016. [Online]. Available: http://bit.ly/2bg2MON. [Accessed 13 January 2017].
15. D. Bertoncello and D. Wee, “Ten ways autonomous driving could redefine the automotive world,” McKinsey & Company, New York, 2015.
16. W. Zhang, S. Guhathakurta, J. Fang and G. Zhang, “Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach,” *Sustainable Cities and Society,* vol. 19, pp. 34-45, 2015.
17. A. Brown, J. Gonder and B. Repac, “An Analaysis of Possible Energy Impacts of Automated Vehicle,” in *Road Vehicle Automation*, New York, Springer International, 2014, pp. 137-153.
18. J. Anderson, N. Kalra, K. Stanley, P. Soensen, C. Samaras and O. Oluwatola, “Autonomous Vehicle Technology: A Guide for Policymakers,” RAND Corp., Santa Monica, 2016.
19. D. Fagant and K. Kockelman, “Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations,” Eno Center for Transportation, Washington DC, 2013.
20. K. Spieser, K. Treleaven, R. Zhang, E. Frazzoli, D. Morton and P. Marco, “Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore,” in *Road Vehicle Automation*, New York, Springer, 2014, pp. 229-261.
21. C. Harper, C. Hendrickson, S. Mangones and C. Samaras, “Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly, and people with travel-restrictive medical conditions,” *Transportation Research Part C,* vol. 72, pp. 1-9, 2016.
22. D. Fagant and K. Kockelman, “The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios,” *Transportation Research Part C,* vol. 40, pp. 1-13, 2014.
23. J. Gonder, M. Earleywine and W. Sparks, “Analyzing Vehicle Fuel Sacing Opportunities through Intelligent Driver Feedback,” SAE International, Warrendale, 2012.
24. C. Wu, G. Zhao and B. Ou, “A fuel economy optimization system with applications in vehicles with human drivers and autonomous cars,” *Transport Research Part D,* vol. 16, pp. 515-524, 2011.
25. A. Talebpour, H. Mahmassani and S. Hamdar, “Multiregime sequential risk-taking model of car-following behaviour,” *Transport Research Record: Journal of the Transportation Research Board,* vol. 2260, pp. 60-66, 2011.
26. Z. Li, M. Chitturi, L. Yu, A. Bill and D. Noyce, “Sustainability effects of next-generation intersection control for autonomous vehicles,” *Transport,* vol. 30, no. 3, pp. 342-352, 2015.
27. M. Gueriau, R. Billot, N.-E. El Faouzi, J. Monteil, F. Armetta and S. Hassas, “How to asses the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies,” *Transportation Research Part C,* vol. 67, pp. 266-279, 2016.
28. H. Weller, L. Jiang and S. Jade, “Powertrain Requirements for major Disruptors: Powertrain Impact through Autonomous Driving,” SAE NAIPC, Warrendale, 2016.
29. A. Davila and M. Nombela, “Sartre - Safe Road Trains for the Environemnt Reducing Fuel Consumption through Lower Aerodynamic Drag Coefficient,” SAE Technical, Warrendale, 2011.
30. J. Cullen, Writer, *4M15 - Sustainable Energy: Transport, vehicles and mobility.* [Performance]. Department of Engineering, University of Cambridge, 2017.
31. A. Freuer and H.-C. Reuss, “Consumption Optimisation in Battery Electric Vehicles by Autonomous Cruise Control using Predictive Route Data and a Radar System,” SAE International, Warrendale, 2013.
32. C. Donna, K. Kockelman and J. Hanna, “Operations of a shared, autonomous, electric vehicle fleet: Implications of vehciel & charging infrastructure decisions,” *Transportation Research Part A,* vol. 94, pp. 243-254, 2016.
33. P. Davis, “Connected/Automated and Autonomous Vehicles (CAVs),” U.S. Department of Energy, Washington DC, 2014.
34. T. Markel, A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik and K. Wipke, “ADVISOR: a systems analysis tool for advanced vehicle modeling,” *Journal of Power Sources,* vol. 110, pp. 255-266, 2002.
35. Wikipedia contributors, “Kaya identity,” Wikipedia, 16 April 2017. [Online]. Available: http://bit.ly/2qeuS5U. [Accessed 25 May 2017].
36. Vehicle Statistics, *Table VEH0120: Licensed vehicles by make and model: Great Britain and United Kingdom,* London: Department for Transport, 2016.
37. World Auto Steel, “Progress in Weight Loss Steel: Body Structures Keep the Slimming Trend Going,” World Auto Steel, 10 January 2011. [Online]. Available: http://bit.ly/2qpLibu. [Accessed 13 December 2017].
38. J. Meiners, “Volkswagen L1 Concept,” Car and Driver, September 2009. [Online]. Available: http://bit.ly/2qoejTw. [Accessed 16 May 2017].
39. K. Tadakuma, T. Doi, M. Shida and K. Maeda, “Prediction formula of Aerodynamic Drag Reduction in Multiple-Vehicle Platooning Based on Wake Analysis and On-Road Experiments,” SAE International, Warrendale, 2016.
40. M. Zabat, N. Stabile, S. Frascaroli and F. Browand, “The Aerodynamic Performance of Platoons: Final Report,” University of California, Berkeley, 1995.
41. Atkins, “Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow,” Department for Transport, London, 2016.
42. Volkswagen, “The new Volkswagen XL1 Super Efficient Vehicle (SEV),” Volkswagen, February 2013. [Online]. Available: http://bit.ly/1g8Vv1A. [Accessed 17 May 2017].
43. G. Eaton, “Sub-national road transport consumption statistics, 2005-2014,” Department of Energy & Climate Change, London, 2015.
44. S. Forden, *UK Government GHG Conversion Factors for Company Reporting,* London: Department of Energy & Climate Change, 2016.

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Definitions/Abbreviations

CAV	Connected and Autonomous Vehicle
IC	Internal Combustion
DARPA	Defense Advanced Research Projects Agency
NREL	National Renewable Energy Laboratory
CFD	Computational Fluid Dynamics
HGV	Heavy Goods Vehicle
BEV	Battery Electric Vehicle
DC	Drive Cycle
NEDC	New European Drive Cycle
RDE	Real Driving Emissions
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
GHG	Greenhouse Gas