WMG
THE UNIVERSITY OF WARWICK

Cost-benefit Considerations

TO ENABLE A CONNECTED TRAFFIC ENVIRONMENT IN THE UK

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UK CITE
CONNECTED INTELLIGENT TRANSPORT ENVIRONMENT

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Glossary

3GPP	3rd Generation Partnership Project
ADAS	Advanced Driver Assistance Systems
AEV	Automated and Electric Vehicles
AOR	Area of relevance
CAV	Connected and Autonomous Vehicles
CCAV	Centre for Connected and Autonomous Vehicles
DARPA	US Defence Advanced Research Projects Agency
DfT	Department for Transport
DSRC	Dedicated Short-Range Communication
DVSA	Driver and Vehicle Standards Agency (DVSA)
EEBL	Emergency Electronic Brake Light
ETSI	European Telecommunication Standards Institute
EU	European Union
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISO	International Organisation for Standardisation
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
LTE	Long-Term Evolution
OBU	On-board unit
RSU	Roadside Unit
SAE	Society for Automotive Engineers
TCW	Traffic Condition Warning
TMS	Traffic Management System
UKCITE	UK Connected Intelligent Transport Environment
UNECE	United Nations Economic Commission for Europe
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VCA	Vehicle Certification Agency

UK Connected Intelligent Transport Environment (UK CITE) aimed to create the most advanced environment for testing connected and autonomous vehicles. It involved equipping over 40 miles of urban roads, duel-carriageways and motorways with a combination of multiple wireless technologies, enabling seamless connectivity across the corridor. The project has established wireless technologies across roads that can improve journeys, reduce traffic congestion and provide entertainment and safety services through better connectivity. The UK CITE project was a collaboration between Visteon Engineering Services Ltd, Jaguar Land Rover Ltd, Coventry City Council, Siemens, Vodafone Group Services Ltd, Huawei Technologies (U) Co Ltd, HORIBA MIRA Ltd, Coventry University, University of Warwick (WMG), Transport for West Midlands and Highways England Company Ltd., co-funded by Innovate UK.

1. Introduction

Adoption of Intelligent Traffic Systems (ITS) has been a subject of great interest both in the UK and internationally. Following this interest, UK CITE was a UK government-funded project that investigated potential communication technologies between vehicles and some other entities and assesses the functionality, safety and convenience of connected and autonomous vehicles. It was a versatile project, looking at the implementation of these technologies from various perspectives, such as technology maturity, cybersecurity, testing methodologies and wider economic and societal implications. This report comprises the identification of measurable benefits of transforming the UK's established road network into a Connected and Intelligent Transportation Environment.

The relationship between cost and expected benefits is often analysed to determine if the benefits of a project or action plan exceed the correlated costs. Decision makers can assess the desirability of a project by quantifying and monetising the benefits and costs, and hence the net result of any investment. Based on the availability of the information, different approaches are recommended:

Table 1. 1 Approaches in cost-benefits considerations

APPROACH	EXPLANATION
Cost-Benefit Analysis	Used when standard monetary values are available
Cost-Effectiveness Analysis	Used when monetary values are available only for costs, but a single measureable impact of the project is achieved
Multi Criteria Analysis	Used when monetary values are not available for major impacts

The cost-benefit consideration of this report uses the second approach: Cost-Effectiveness Analysis, due to the difficulties in determining monetary impacts of the benefits at this stage. Even though every benefit indicator can be turned into a monetised version, it was determined that it was not suitable to evaluate the cost-benefit balance of this industry with only an economic comparison; saved lives, decreased injuries, safer roads, better travel experiences, greener environment and some other similar beneficial impacts are compulsory to mention and add to the comparison. This kind of approach is also recommended by the UK and Australia governments[1].

The report aims to fulfil the following objectives:

- To consider a comprehensive range of perspectives of the validated benefits of the adoption of Connected and Autonomous Vehicle (CAV) technologies.
- To enhance the understanding of potential benefits and illuminate the areas which have the most growth potential.
- To calculate the anticipated costs of implementation and operation of the CAV technologies.
- To scale the cost of adopting the aforementioned technologies across the UK road network.

By these means, the report seeks to answer the questions "Why is the project essential for public and future social life?" and "What is the approximate cost to stakeholders?".

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[1] Tomecki, A.B., Yushenko, K. and Ashford., A. (2016). Considering a cost-benefit analysis framework for intelligent transport systems.

2. Benefit Configuration of the UK CITE

2.1 Benefit Dimensions

Intelligent Traffic Systems (ITS) primarily aim to achieve four main types of benefits: enhanced mobility, decreased environmental impacts and increased safety and economic benefits[2,3,4,5]. However, the research conducted by UK CITE excluded directly considering economic benefits, instead regarding them as indirect impacts resulting from the other benefit dimensions, and focused on the transformative impacts of those technologies adopted for safety, mobility and a greener environment. (Figure 2.1).

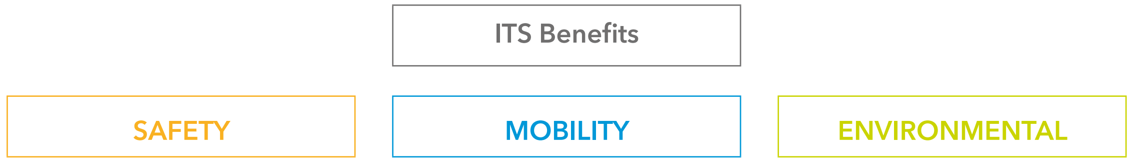
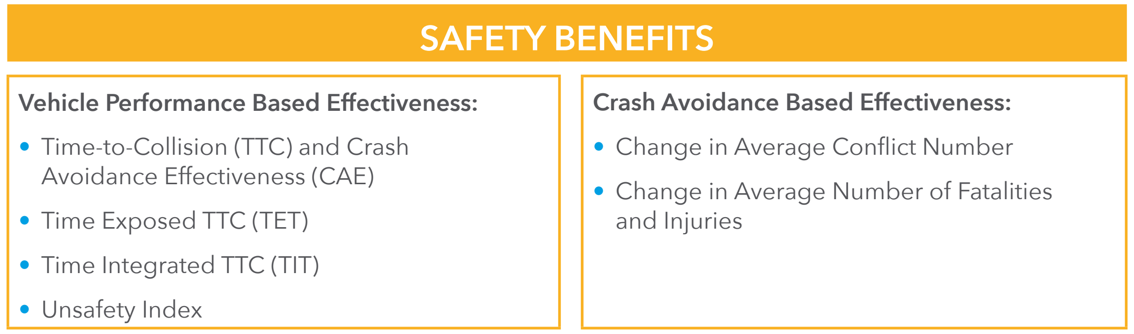


Figure 2. 1 ITS Benefits

2.1.1 Safety Benefits

Connected vehicle (CV) technology and driving assistance (DA) technology showcase an opportunity to have a great impact on traffic safety. Evidence[6] shows that 94% of public roadway crashes involve some element of human error, either as the sole significant culprit or in combination with other factors. The advancement of the CV and DA technologies can mitigate the adverse effects of drivers' errors, enabling various benefits such as collision reduction through the announcement of the presence of a vehicle to the surrounding environment by vehicle to vehicle (V2V) and/or vehicle to infrastructure (V2I) communication[3].

This study examines the safety effectiveness of the CV and DA technologies in two categories: crash-avoidance-based effectiveness and vehicle-performance-based effectiveness. While the crash-avoidance-based effectiveness measures the number of conflicts and near-crash events in a real-world environment to reveal the crash reduction effectiveness, vehicle-performance-based effectiveness uses metrics such as speed, headways, rejected gaps, time-to-collision, conflict rates, etc., to enable the performance of the measurement on a simulation environment without directly connecting the CV and DA technologies with reduced crash incidents. Each of the elements listed in Figure 2.2 in each of these two categories are explained further below.



SAFETY BENEFITS

Vehicle Performance Based Effectiveness:

- Time-to-Collision (TTC) and Crash Avoidance Effectiveness (CAE)
- Time Exposed TTC (TET)
- Time Integrated TTC (TIT)
- Unsafety Index

Crash Avoidance Based Effectiveness:

- Change in Average Conflict Number
- Change in Average Number of Fatalities and Injuries

Figure 2. 2 Safety Benefits

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[2] Tian, Danyang and Wu, Guoyuan and Boriboonsomsin, Kanok and Barth, Matthew. (2017). A co-benefit and tradeoff evaluation framework for connected and automated vehicle applications.

[3] Chandra, S. and Camal, F. (2016). A simulation-based evaluation of connected vehicle technology for emissions and fuel consumption. Procedia Engineering, 145, pp.296-303.

[4] US Department of Transportation, Research and Innovative Technology Administration (RITA). (2011). Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned Desk Reference: 2011 Update.

[5] Mangones, S.C., Fischbeck, P. and Jaramillo, P. (2017). Safety-related risk and benefit-cost analysis of crash avoidance systems applied to transit buses: comparing New York City vs. Bogota, Colombia. Safety science, 91, pp.122-131.

[6] US Department of Transportation. (2015). Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey.

i. Vehicle Performance Based Effectiveness

The vehicle-performance-based effectiveness aims to provide more accurate safety metrics by evaluating the possible control strategies. These safety indicators are used in a simulation environment to measure the likelihood of an incident. Time to Collision (TTC), Extended Time to Collision (comprising Time Exposed TTC (TET) and Time Integrated TTC (TIT)) and the Unsafety Index constitute the most accepted indicators[7]. In addition to the fundamental explanations provided below, formulas related to each performance indicator are provided in the appendix.

a. Time-to-Collision (TTC) and Crash Avoidance Effectiveness

TTC is defined as the time to a collision of two cars travelling in the same direction if they maintain their direction and speed. It is accepted as a traffic safety and risk indicator, where a low TTC value means a higher risk of accident and high TTC value means a lower risk of accident[8].

If the TTC of a vehicle decreases below a certain critical value, it is accepted as a potentially unsafe occasion i.e a 'conflict situation'. Previous research[9,10] presents various perspectives for that critical value (denoted TTC*) of which the average for moderate risk level is 1.5 seconds. Here in Figure 2.3 we have an example journey of a vehicle, where the vehicle has dropped below the threshold TTC value twice, hence giving two 'conflicts'[8] over this journey.

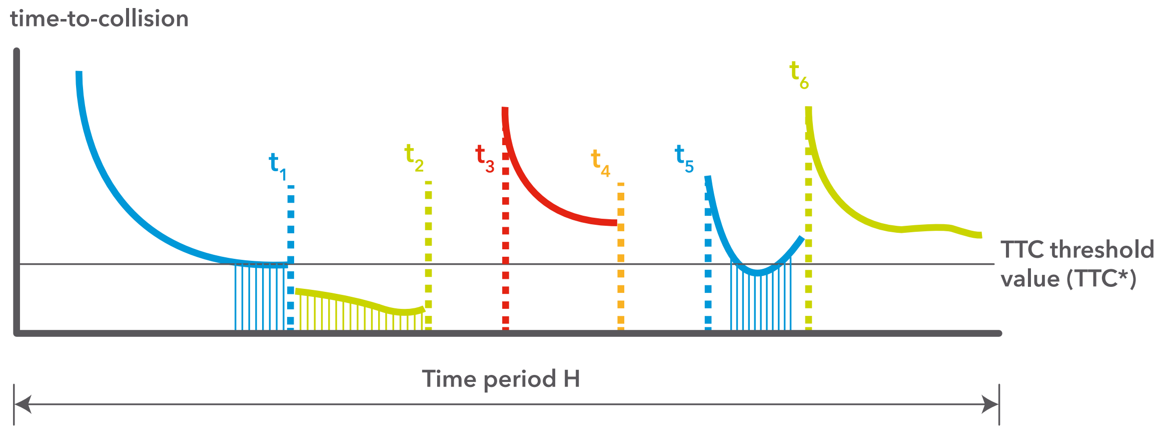

Figure 2.3 A TTC sample of a vehicle[9].

In order to use TTC as a safety measurement, an incident probability figure can be produced by considering the number of cars braking when they are under TTC* (i.e when TTC test < TTC*) as a proportion of all braking moments. The improvement can be observed in the decrease of this probability[11].

As a next step, in order to observe the effectiveness of an implemented technology, crash avoidance effectiveness can be utilised to proportion the incident probability before and after the technology adoption[7].

b. Time Exposed TTC (TET)

The TTC measure has two extended versions which increase the detail of the measurement. The first is Time Exposed TTC (TET), which refers to the length of time that vehicles are below the TTC* threshold value[9]. The sum of the dashed moments in Figure 2.3 illustrate the TET of the vehicles in that traffic environment. Hence, we can infer that the lower the TET, the less time the vehicles are in a conflict risk and so the safer the situation is[8].

[7] Olia, A., Abdelgawad, H., Abdulhai, B. and Razavi, S.N. (2016). Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives. Journal of Intelligent Transportation Systems, 20(3), pp.229-243.

[8] Dijkstra, A., and Drolenga, H. (2008). Safety effects of route choice in a road network: Simulation of changing route choice (Vol. 2008, No. 10). SWOV Institute for Road Safety Research.

[9] Minderhoud, M.M. and Bovy, P.H. (2001). Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention, 33(1), pp.89-97.

[10] Van der Horst, A. R. A. (1991).Time-to-collision as a Cue for Decision-making in Braking. 475 Vision in vehicles 3: 19-26

[11] Sam Doecke, Alex Grant and Robert W. G. Anderson. (2015). The Real-World Safety Potential of Connected Vehicle Technology, Traffic Injury Prevention, 16:sup1, S31-S35.

c. Time Integrated TTC (TIT)

Although TET brings an advanced level of detail in addition to the standard TTC, it still has its own disadvantage, namely being incapable of measuring the variation of TTC values which are lower than TTC*; TET cannot differ the danger levels of two TTC measures which both are below TTC*. For example, two TTC measures which last the same length but one is at the TTC value of 1 second and the other is 0.5 would both give the same TET values. Hence, Time Integrated TTC (TIT) is used in order to include the risk weight of TTC cases[8].

d. Unsafety Index

In the Unsafety Index, the level of "unsafety" of two consecutive vehicles, is determined during each simulation step by the position, speed and maximum braking capacity of a specific vehicle. If a crash does not occur, the unsafe parameter value is zero. To provide a more holistic view of the network, the unsafety parameters can be calculated for each link of the microsimulation model network at key time intervals and aggregated to provide the unsafe density (detailed further in the appendix). This enables the comparison of safety level between different links of the network as well as the observation of how it changes from one time-period to another[9].

ii. Crash Avoidance Based Effectiveness

The crash-avoidance-based effectiveness assumes that the occurrence of a collision in the real world is a rare phenomenon. Hence, for the measurement of the effectiveness of CV and AD technology as a prevention mechanism that can reduce crash incidents, conflict rates and near-crash events are employed as a common measurement.

a. Change in Average Conflict Number

The Change in Average Conflict Number measures the difference in the average conflict number among time periods or varied penetration levels. This measure usually requires real-life data for a time period, but since CAV technologies have not yet been tested in a real life environment to provide sufficient data, simulation data is used for the purpose of this study. One drawback of this measurement in the context of this study is that the chosen software VISSIM does not reflect the time that the traffic stops and the reduction in speed when a crash has occurred[2,7].

b. Change in Average Number of Fatalities and Injuries

Improving road safety with the help of CAV technologies will also reduce the number of fatalities and injuries. This can result from fewer crashes occuring, but also by having reduced impact speeds which lessens the probability of fatality and injury. Previous research[13,34] has found that adoption of CAV technologies can decrease fatal and non-fatal crashes by varying proportions. The U.S. Department of Transport has also discovered essential crash reductions for two specific technology use cases: intersection movement assist and left turn assist[11].

[2] Tian, Danyang and Wu, Guoyuan and Boriboonsomsin, Kanok and Barth, Matthew. (2017). A co-benefit and tradeoff evaluation framework for connected and automated vehicle applications.

[7] Olia, A., Abdelgawad, H., Abdulhai, B. and Razavi, S.N. (2016). Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives. Journal of Intelligent Transportation Systems, 20(3), pp.229-243.

[8] Dijkstra, A., and Drolenga, H. (2008). Safety effects of route choice in a road network: Simulation of changing route choice (Vol. 2008, No. 10). SWOV Institute for Road Safety Research.

[9] Minderhoud, M.M. and Bovy, P.H. (2001). Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention, 33(1), pp.89-97.

[11] Sam Doecke, Alex Grant & Robert W. G. Anderson. (2015). The Real-World Safety Potential of Connected Vehicle Technology, Traffic Injury Prevention, 16:sup1, S31-S35.

[13] Penmetsa, P., Hudnall, M., & Nambisan, S. (2019). Potential safety benefits of lane departure prevention technology. IATSS Research, 43(1), 21-26.

[34] Li, T., & Kockelman, K. M. (2016, January). Valuing the safety benefits of connected and automated vehicle technologies. In Proceedings of the 95th Annual Meeting of the Transportation Research Board, Washington, DC, USA (pp. 10-14).

2.1.2 Mobility Benefits

The second spectrum of gains from the utilisation of CV and DA technologies refers to mobility benefits. The exploration of methods and management strategies through mobility-oriented applications aims to improve operational efficiency and individual mobility. Multiple studies[12,14,15] have shown that traffic congestion is the culprit to blame for huge costs due to wasted time, fuel consumption, and business fees arising from delayed deliveries. In response to these problems, CAV technology is proposed as a potential means to ease traffic congestion and travel delay by creating a safe and interoperable connected vehicle network, enabling system operators to improve the transportation system and, thus, overall mobility. Moreover, vehicle-to-everything (V2X) communication will improve comfort for the vehicle user since the autonomous vehicle will be able to adjust its speed smoothly to the conditions that appear on the road (e.g. speed of traffic, precise knowledge of when traffic lights change).

iii. Travel Time Improvement

Mobility benefits with the use of V2X applications have been demonstrated in multiple studies[15,16]. Improvement in travel time is a prospective outcome of a driver's enhanced decisions through real-time guidance and rerouting in the connected vehicle environment due to real-time information sharing about traffic incidents, lane closures, construction zones and so forth[5,16,17].

iv. Increase in Average Speed

Using another perspective of this standard measurement, the average speed can be examined to reveal and reframe the mobility benefits from CV and DA technologies[2,18].

2.1.3 Environmental Benefits

It is widely accepted that transportation is one of the largest contributors to air pollution and greenhouse gas emissions. The most significant pollutants of vehicle operations are carbon monoxide (CO), carbon dioxide (CO2), volatile organic compounds (VOCs) or hydrocarbons (HC), nitrogen oxide (NOx), and particulate matter (PM) among others, and constitute a threat to human health and are a leading cause of environmental degradation. Despite the technological improvements which have been made in combustion systems and vehicle electrification, the problem persists. CAV technologies are expected to lead the way by decreasing congestion, directly impacting emissions from acceleration and deceleration, and by enabling drivers and transportation managers to make greener choices through re-routing by exploiting real-time data. The measurement of the impact is performed by two indicators: average fuel consumption and emissions level[2,19,20].

i. Reduction in Fuel Consumption

To measure the environmental benefits of CAV technologies, the achieved reduction of average fuel consumption as the penetration of CAVs increase is a relevant indicator.

ii. Reduction in Greenhouse Gas (GHG) Emissions and Air Pollutants

Moreover, the reduction in harmful emissions can also be used to measure the benefits of CAV technologies.

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[2] Tian, Danyang & Wu, Guoyuan and Boriboonsomsin, Kanok & Barth, Matthew. (2017). A co-benefit and tradeoff evaluation framework for connected and automated vehicle applications.

[5] Mangones, S.C., Fischbeck, P. and Jaramillo, P. (2017). Safety-related risk and benefit-cost analysis of crash avoidance systems applied to transit buses: comparing New York City vs. Bogota, Colombia. Safety science, 91, pp.122-131.

[12] Errampalli, M., Senathipathi, V., & Thamban, D. (2015). Effect of congestion on fuel cost and travel time cost on multi-lane highways in India. IJTTE, 5(4), 458-472.

[14] https://www.economist.com/graphic-detail/2018/02/28/the-hidden-cost-of-congestion

[15] SMMT International Automotive Summit. CONNECTED AND AUTONOMOUS VEHICLES. Revolutionising Mobility in Society.

[16] Jadaan, K., Zeater, S. and Abukhalil, Y. (2017). Connected Vehicles: An Innovative Transport Technology. Procedia Engineering, 187, pp.641-648.

[17] Wang, M., Daamen, W., Hoogendoorn, S. and Van Arem, B. (2011). Estimating acceleration, fuel consumption, and emissions from macroscopic traffic flow data. Transportation Research Record, 2260(1), pp.123-132.

[18] Huguenin, F., Torday, A. and Dumont, A. (2005). March. Evaluation of traffic safety using microsimulation. In Proceedings of the 5th Swiss Transport Research Conference–STRC, Ascona, Swiss.

[19] Shridhar Bokare, P. and Kumar Maurya, A., (2013). Study Of Effect Of Speed, Acceleration And Deceleration Of Small Petrol Car On Its Tail Pipe Emission. International Journal for Traffic & Transport Engineering, 3(4).

[20] Ma, J., Zhou, F. and Demetsky, M.J. (2012) April. Evaluating mobility and sustainability benefits of cooperative adaptive cruise control using agent-based modeling approach. In Systems and Information Design Symposium (SIEDS), 2012 IEEE (pp. 74-78). IEEE.

2.2 Complexities and Challenges

2.2.1 Contextual Complexities

Traffic is a complex concept, mainly due to its numerous variations regarding the scenarios and parties involved. When contemplating an improvement in any aspect of the traffic, ideally all of these variations should be considered to reach the best results. However, to test and measure such a complex network of possibilities has inherent difficulties, such as lack of data or measurement capability. Assumptions are necessary for unknown variables in order to achieve the best results possible within that predefined framework.

An essential intricacy of studies in the fields of Intelligent Traffic Systems (ITS) and CAV technologies relates to the vehicle types involved in the benefit measurements. The benefits may vary when different vehicle types are examined, for example comparing fuel consumption between trucks and cars. In another example, the difference of speed limits among the different types of vehicles impacts the total holistic behaviour of the traffic. Since it was not possible to accurately observe these changing influences with the data and resources available to the UK CITE project, it was decided to disregard the impact of this variability for the study and to adopt a narrower focus to identify the safety, mobility and environmental benefits of CAV technologies by examining only cars.

Another similar complexity is about the types of crash. Crash avoidance technologies perform differently under different crash types. Therefore, the benefits of particular use cases vary according to the crash type involved. For this study, to avoid complexities that would influence the ability to compare the results of the simulation, only one crash type has been used: a car to car collision where the front of the rear vehicle impacts the back of the car in front. Parties that are involved in the collision can differ. For example, in police reports, four groups are identified: motorist, passenger, cyclist, and pedestrian. In this study, the crash incidents focus only on the two vehicles that are involved[5].

In several instances, it is hard to measure the net impacts of technologies implemented, especially when there are interrelations between the examined elements. These interrelationships can be revealed in synergetic or antagonistic mechanisms. For example, GHG emissions, which are an indicator of the environmental benefits, are a function of congestion, and if congestion decreases due to the utilisation of CAV technologies revealing a mobility benefit, GHG emissions decrease as well. On the other hand, in the case of decreased travel time due to rerouting, the behavioural change of the driver towards more aggressive driving and the increased speed may result in higher emissions and fuel consumption. This study has observed the separate impacts of use cases as a starting point[2]. However, any potential synergetic and antagonistic impacts of adopted technologies should be in focus for future studies.

A similar approach to the issue is to look at the impacts of use cases when they are utilised together[21]. Two methods are found in the literature: the relational effect and the combined effect[2,21]. In the first of the two, a comparison of the benefits of the three aspects of safety, mobility and environment is conducted based on the results of a single simulation. The second method proposes testing the cooperative effects of use cases. Since these technologies are parts of a holistic project and will be in use altogether, it was considered more appropriate to look at those technologies' combined influence on the behaviour and travel quality of the driver in traffic for the purposes of this project.

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[2] Tian, Danyang & Wu, Guoyuan & Boriboonsomsin, Kanok & Barth, Matthew. (2017). A co-benefit and tradeoff evaluation framework for connected and automated vehicle applications.

[5] Mangones, S.C., Fischbeck, P. and Jaramillo, P. (2017). Safety-related risk and benefit-cost analysis of crash avoidance systems applied to transit buses: comparing New York City vs. Bogota, Colombia. Safety science, 91, pp.122-131.

[21] Yue, L., Abdel-Aty, M., Wu, Y. and Wang, L. (2018). Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low-level automation systems. Accident Analysis & Prevention, 117, pp.55-64

2.2.2 Practical Challenges

The first practical challenge encountered in the UK CITE project is a shared difficulty with previous research in this area. Given the immaturity of CAV technologies, it is hard to reach real-life data to measure the benefits of their adoption. Even though some datasets were available, it was not possible to obtain the local historical data to benchmark and detect the marginal impacts of CAV technologies.

Hence, a simulation was selected as the only data source for the project, a chief method of benefit measurement in ITS[21]. This has ensured the internal validity of the measurement including the crosschecking of datasets. However, simulation-based benefit measurement methods contain further challenges. Simulations may have limited constructs as they are only a controlled representative of the real world, and the software itself may have an impact on the project with its capabilities or calculation methodologies. In the UK CITE project, VISSIM Traffic Simulation has been used by collaborator MIRA. The software has a ceaselessly moving traffic environment, which does not specifically allow the observance of crashes. Whilst the number of crashes can be measured using each time that a vehicle drives on top of another, it is still not easy to detect the severity of those crashes. Similarly, some fatalities and injuries cannot be detected in the simulation environment.

2.3 Approach

Various data sources have been utilised in the preparation of this report. Starting with a review of existing state-of-the-art research in the field, this exploration has been combined with the dynamics of the UK CITE project. The preparation of the report has taken the following four main stages:

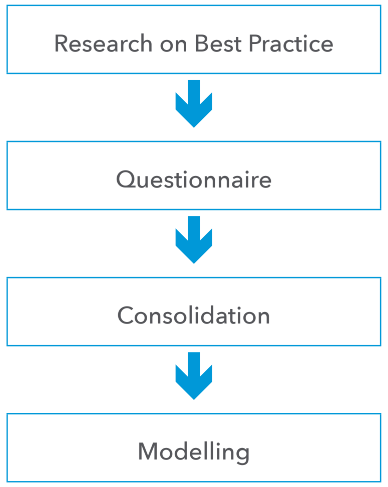

Figure 2.4 Roadmap of the research

In the first stage, comprehensive and thorough research was undertaken over both academic and practical resources. This helped to frame the study for both perspectives. Then, stakeholders' ideas were requested on the suitability of this framework via a questionnaire and a subsequent web-based panel. Hence, a revised list was produced, followed by a second round of stakeholder consultation. But this time, only specific stakeholders were included in the process, who could directly provide data for the measurements. In the last stage, a simulation-based measurement has been evaluated as a suitable method to measure benefits, and moreover, we had observed that in all benefits categories we had suitable performance indicators (PIs) that could be tested via a simulation platform. Two primary performance indicators for each benefit category were selected for measurement, as seen in Table 2.1.

BENEFIT CATEGORY	PRIMARY INDICATOR 1	PRIMARY INDICATOR 2
Safety	Crash Avoidance Effectiveness	Average Conflict number
Mobility	Average Speed	Total Travel Time
Environmental	Fuel Consumption	CO Emission

Table 2. 1 Primary performance indicators for each benefit category

In addition to the performance indicators, for validity, the following assumptions were made:

ASSUMPTIONS AND MODELLING CRITERIA	FACTORS
Use Cases	• EEBL (Emergency Electronic Brake Lights) • EVW (Emergency Vehicle Warning) • TCW (Traffic Condition Warning) • RWW (Roadwork Warning)
Road Types	• Motorway • Urban
Traffic Density	• Light (1,000 for Motorway, 300 for Urban) • Medium (3,000 for Motorway, 600 for Urban) • Heavy (5,000 for Motorway, 900 for Urban)
Technology Penetration	• Baseline (below 10%) • Low (11-40%) • Medium (41-70%) • High (71-100%)

Table 2. 2 Assumptions and modelling criteria

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[21] Yue, L., Abdel-Aty, M., Wu, Y. and Wang, L. (2018). Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low-level automation systems. Accident Analysis & Prevention, 117, pp.55-64.

2.4 Impact Analysis of CAV Adoption

Impacts of CAV technologies were analysed at varying technology penetration levels for urban and motorway road environments, in line with the assumptions and limitations noted in the previous section.

2.4.1 Emergency Electronic Brake Lights (EEBL)

The use case of Emergency Electronic Brake Lights is expected to reveal safety benefits as the adoption of CAV technologies increases since the driver is informed and given more time to react to incidents occurring (where the front vehicle or vehicles suddenly adjust their speed or stop). Hard braking with deceleration of over 4m/s^2 initiates the EEBL which provides the warning about the deceleration rates of vehicles and safe distance notifications. Since the nature of the use case is about a developing need of braking activity, safety-related improvements can be expected to be the primary focus of the use case in comparison to the other two benefit categories.

In the motorway environment, a near five-fold increase was observed in the Crash Avoidance Effectiveness Index between the medium and high penetration levels, building on the gain already seen between Baseline – Low, and Low – Medium, levels. A reduction can also be seen in the Average Conflict Number as the penetration of CAVs increases. Table 2.3 clearly illustrates that the benefits of this use case manifest within the safety category, and that an impact on safety can be observed even at the very lowest technology penetration.

		Safety		Mobility		Environmental	
	Penetration Level	Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
Motorway	**BASELINE**	0	91	57	198	0.085	1.576
	LOW	3.40	84	56	199	0.086	1.582
	MEDIUM	5.86	73	56	199	0.086	1.580
	HIGH	28.64	71	56	199	0.086	1.579

Table 2. 3 EEBL Benefits Analysis in Motorway Environment

In the urban environment a similar trend continues (Table 2.4), with steady improvement shown in the Crash Avoidance Effectiveness and with fewer average conflicts. As with the motorway environment, the use case demonstrates its influence most within the safety benefits category, with further benefits seen in CO Emissions where a decrease is realised relative to the increasing level of adoption of CAV technology.

		Safety		Mobility		Environmental	
	Penetration Level	Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
Urban	**BASELINE**	0	674	25	221	0.057	1.057
	LOW	2.49	645	25	222	0.057	1.055
	MEDIUM	3.55	625	25	222	0.057	1.050
	HIGH	5.86	638	25	220	0.057	1.045

Table 2. 4 EEBL Benefits Analysis in Urban Environment

Overall, in both motorway and urban environments, the EEBL application impacts most by increasing the safety of roads, reducing the average number of conflicts and having higher effectiveness indexes for avoiding crashes. For the urban environment, by triggering fewer requirements for sudden braking, the EEBL use case decreases the overall acceleration and deceleration behaviour and hence results in a reduced amount of CO emissions. This reduction is boosted with the higher adoption rates of the CAV technologies.

2.4.2 Emergency Vehicle Warning (EVW)

The purpose of the Emergency Vehicle Warning (EVW) is to secure an uninterrupted movement of emergency vehicles, helping them to arrive at their destination sooner. By receiving the signal (either directly between vehicles or via a Roadside Unit) of an emergency vehicle approaching from behind, drivers can prepare themselves earlier to give way. Therefore, we can say that the benefits will not be realised for the connected vehicles or the traffic itself, but through their actions the emergency vehicle will decrease its travel time, leading to multiple benefits for society. A slight improvement in the mobility of such an emergency vehicle can prove crucial for the outcome of an incident. Therefore, direct safety, mobility and environmental benefits within the setting of the examined measurements were not expected.

		Mobility			Mobility	
	Penetration Level	EV Travel Time (sec)	EV Delay Time (sec)		EV Travel Time (sec)	EV Delay Time (sec)
Motorway	**BASELINE**	160	10	Urban	233	113
	LOW	160	10		234	114
	MEDIUM	161	11		232	112
	HIGH	159	9		228	108

Table 2.7 EVW Benefits Analysis in Urban Environment

The emergency vehicle (EV) travel time showed that the mobility of the emergency vehicle (EV) is improved, but the significance of the improvement is not clearly statistically relevant. It should be kept in mind that this case is different to other use cases as it is more than a warning, but an interactive case with a very particular class of vehicle as the subject. The main purpose of EVW is for the car or driver to know to move out of the way, safely, with more prior warning than may normally be provided by the audible siren. One particular area of interest for this unique case is behaviour at traffic lights, for which more detailed study is required.

2.4.3 Traffic Condition Warning (TCW)

Traffic Condition Warning (TCW) provides enhanced notice to drivers about any incident ahead that can change the flow of traffic. Examples include heavy traffic congestion, the end of a static queue, or slow-moving traffic, allowing drivers to adjust their speed accordingly. Signalling the connected vehicles about the current traffic flow enables them to brake earlier and more progressively, promoting a safer traffic flow. The initial expectation for the TCW use case was that it would lead to benefits for all three examined aspects due to improved traffic flow. The main expected outcome of the warning was to decrease the number of crashes at the end of queues, hence increasing the crash avoidance effectiveness. Even though it is a similar case to EEBL, TCW warnings can notify drivers earlier than EEBL and are triggered in a wider range of cases. Therefore, the use case was expected to have a significant impact on all benefit categories due to the smoother traffic flow and more stable speeding behaviour.

In motorway simulations (Table 2.8), the insignificant number of conflicts in this road type is again an inhibitor for the extraction of reliable results about the safety benefits for the TCW use case. Moreover, mobility and environmental measurements are consistent regardless of the CAV technologies penetration level. Thus, no significant mobility or environmental benefits were noted in the TCW use case.

Motorway	Penetration Level	Safety		Mobility		Environmental	
		Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
	BASELINE	0	7	56	199	0.085	1.573
	LOW	-13.11	7	56	200	0.085	1.571
	MEDIUM	-14.44	9	56	202	0.085	1.570
	HIGH	10.78	7	55	202	0.085	1.568

Table 2.8 TCW Benefits Analysis in Motorway Environment

In the urban road network (Table 2.9), gradual improvement can be observed in both safety indicators. The highest safety benefits of the TCW application are realised at the highest adoption level of CAV technologies. Regarding mobility and environmental benefits, however, only a slight decrease in CO emission is observed for the highest adoption rate. Specifically, these impacts were perceived in light traffic conditions where around 300 vehicles commuted.

Urban	Penetration Level	Safety		Mobility		Environmental	
		Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
	BASELINE	0	310	24	230	0.046	0.842
	LOW	2	308	24	230	0.046	0.842
	MEDIUM	6	300	24	230	0.046	0.840
	HIGH	17	292	24	230	0.045	0.833

Table 2.9 TCW Benefits Analysis in Urban Environment

To summarise, the most remarkable benefits were gathered in the safety category given the increased awareness of the driver for the surrounding environment and their ability to react. This decreased the number of crashes at the end of queues by a significant proportion, which in turn increased the effectiveness of the crash avoidance during the commute. Contrary to the expectations of the scenario, improvements were realised neither for mobility nor environmental performance indicators within both road environments within this simulation. The greatest changes occurred in light traffic conditions; however, in terms of mobility, the biggest benefits are expected to be achieved in high traffic density. Hence we can infer that TCW application is either not the best solution for mobility problems or it requires complementary technologies to reach its best performance. As mentioned earlier, performance of the CAV technologies are changeable when they are supported with other technologies[21].

2.4.4 Roadwork Warning (RW)

The use case of Roadwork Warning (RW) refers to the warning of drivers to any works taking place on the road affecting traffic, for example the closure of a traffic lane or a request or stipulation to temporarily reduce speed for safety reasons. One expected outcome of this application for the connected vehicles was to avoid the number of conflicts caused by roadworks, similar to the effect of TCW in dangerous end-of-queues. RW may also enable an improvement in the travel time of drivers with the early warning about lane utilisation.

Similar to previous use cases, in a motorway environment, it is difficult to get inferences for safety due to the low number of crashes (Table 2.10). For the other two examined aspects, the increased adoption of CAV technologies did not make any significant difference in mobility or environmental measures in the motorway environment.

Motorway	Penetration Level	Safety		Mobility		Environmental	
		Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
	BASELINE (0%)	0	3	56	199	0.085	1.572
	LOW	-1	5	56	200	0.085	1.570
	MEDIUM	-38	9	55	202	0.085	1.570
	HIGH	-5	6	55	202	0.085	1.568

Table 2.10 RWW Benefits Analysis in Motorway Environment

On urban roads, steady improvement was recorded as the CAV technologies are installed in more vehicles for the safety benefits (Table 2.11). The warning of roadworks was shown to decrease conflict and increase crash avoidance effectiveness in all traffic conditions, leading to improved safety for both road users and road workers. Interestingly, environmental benefits are achieved with this application as the adoption of CAV technologies increases. The environmental benefits refer to the significant reduction of GHG emissions and have the most significant impact of all use cases and road types.

Urban	Penetration Level	Safety		Mobility		Environmental	
		Crash Avoidance Effectiveness (#)	Average Conflict Number (#)	Average Speed (mph)	Total Travel Time (sec)	Fuel Consumption (l/km per vehicle)	CO Emission (g/km per vehicle)
	BASELINE (0%)	0	309	24	230	0.045	0.842
	LOW	8	298	24	230	0.045	0.832
	MEDIUM	16	285	24	231	0.044	0.819
	HIGH	20	274	24	232	0.044	0.808

Table 2.11 RW Benefits Analysis in Urban Environment

To conclude, significant impacts of the Roadwork Warning use case were detected in the urban environment, with a highly significant decrease in the number of average conflicts and an important reduction of CO emissions. Similarly to TCW, combining the use case with some other additional technologies may create an extensive amount of benefits for average travel time.

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[21] Yue, L., Abdel-Aty, M., Wu, Y. and Wang, L. (2018). Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low-level automation systems. Accident Analysis & Prevention, 117, pp.55-64

2.4.5 Summary

Overall, safety benefits are expected from the adoption of CAV technologies in all of the use cases for the urban environment. Specifically, the increased safety as indicated by the increased crash avoidance effectiveness and the decreased average conflict numbers were proportional to the gradual increase of CAV technologies penetration level for the EEBL (Emergency Electronic Brake Lights), TCW (Traffic Condition Warning) and RW (Roadwork Warning) applications while no consistent trends were observed for the EVW (Emergency Vehicle Warning) use case. The greater number of crashes as a reference point for an urban environment increases the reliability of the results from the simulations of this road type.

On the other hand, on a motorway, only the EEBL application recorded a substantial number of crashes, and reduction of those crashes, as a consistent outcome and achieved more significant safety benefits in the motorway environment as the adoption of CAV technologies increased. For the other use cases, the insignificant number of baseline crashes inhibits us from drawing reliable conclusions of CAV technology diffusion with safety in motorways.

In terms of mobility benefits, none of the use cases showed a significant benefit regarding travel time or speed of the vehicle, except a small amount of improvement in the travel time of emergency vehicles.

The environmental aspect observed EEBL and RW use cases recording some impact concerning CO emission as the adoption of the CAV technologies increased.

2.5 Opportunities

Outside of the benefits categories already discussed, there are further opportunities to gain from the aforementioned CAV applications. Overall, the stated use cases have performed an average decrease of 8% on the average crash figures on urban roads; on motorways meaningful data was not obtainable except for the case of EEBL. Although partly a result of the limitations of simulation technology, the low crash figures leading to insignificant data is a recognised phenomenon supported by the UK Department for Transport's 2017 Annual Report[22] which states: "Motorways are statistically the safest roads in GB. The risk of death on motorways was around … 3 times lower than for urban roads".

Statistically, only 6% of vehicle fatalities are from motorway networks, while 32% are from urban, and the remainder (62%) from rural roads. However, in reality, this 6% corresponds to approximately 4,414 accidents that end up with 73 fatalities and 6,625 injuries (of which 534 are serious) for 2,300 miles of UK motorway. After the initial adoption of CAV technologies, when up to 30% of the cars in the traffic adopt the EEBL application, statistically an average of 309 car accidents will be avoided, together with 5 fatalities and 464 injuries (37 serious). At a technology penetration level of 70%, the average reduction of 22% of crashes accomplished by the adoption of the EEBL application means that around 971 accidents can be avoided resulting in 16 saved lives and 1,457 fewer injuries (117 serious) each year. Further, the impact speeds of the remaining accidents will be decreased, reducing the severity of injuries sustained.

In the urban environment (urban "A" roads used in simulation), considerably more accidents occur with average annual totals of 21,309 collisions, 57 fatalities and 16,265 injuries (913 serious injuries). Three of the four use cases provide significant results that represent benefits varying between 5% and 11% according to the penetration levels and the use cases. Applying these to the annual crash figures allows us to quantify and illustrate the real-life impacts. Initially, when only a third of the cars in the traffic adopt CAV technologies, the most critical benefits are observed from the EEBL and RW with 852 avoided collisions, resulting in 2 saved lives and 651 fewer injuries (144 serious). When the penetration level of the CAV technologies is increased above 70%, RW reduces the number of collisions by the highest rate of 11%, which gives a reduction of circa 1,065 of the crashes in urban roads, 6 fewer fatalities and 1,789 fewer injuries (100 serious)[23,24].

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[22] UK Department for Transport. (2017). Reported road casualties in Great Britain: 2017 annual report.

[23] UK Department for Transport. (2015). Facts on Road Fatalities.

[24] UK Department for Transport. (2013). A valuation of road accidents and casualties in Great Britain: Methodology note.

There is, in addition, a financial dimension to these discussions. Value of Statistical Life[25,26] is an instrument to observe these economic impacts. It is accepted as a statistical indicator of the financial value of human life and measured by authorities in proportion to the gross domestic product (GDP) per head. Various techniques can be used for this measurement: one such technique utilised by the DfT in 2016 suggested the value of a prevented (statistical) fatality is £1.83 million[27]. Similarly, the cost of a serious injury has been calculated for 2017 as £205,000 using cost elements such as lost output, medical and ambulance costs and human costs in previous reports[22,24]. Combined with the previous illustrations, the following table (Table 2.11) provides a summary of the opportunities that CAV technologies may bring into everyday lives in the near (low penetration) and distant (high penetration) future.

MOTORWAY

	Use Case	EEBL	TCW	RW		Use Case	EEBL	TCW	RW
Low Penetration	Number of Avoided Accidents	309	-	-	High Penetration	Number of Avoided Accidents	0.045	-	-
	Number of Prevented Serious Injuries	37	-	-		Number of Prevented Serious Injuries	0.045	-	-
	Number of Saved Lives	5	-	-		Number of Saved Lives	0.044	-	-
	Value of Prevented (Statistical) Fatality £	17m	-	-		Value of Prevented (Statistical) Fatality £	54m	-	-

URBAN

	Use Case	EEBL	TCW	RW		Use Case	EEBL	TCW	RW
Low Penetration	Number of Avoided Accidents	852	213	852	High Penetration	Number of Avoided Accidents	1,065	1,279	2,344
	Number of Prevented Serious Injuries	37	9	37		Number of Prevented Serious Injuries	46	55	100
	Number of Saved Lives	2	1	2		Number of Saved Lives	3	3	6
	Value of Prevented (Statistical) Fatality £	12m	3m	12m		Value of Prevented (Statistical) Fatality £	15m	18m	32m

TOTAL

	Use Case	EEBL	TCW	RW		Use Case	EEBL	TCW	RW
Low Penetration	Number of Avoided Accidents	1,161	213	852	High Penetration	Number of Avoided Accidents	2,036	1,279	2,344
	Number of Prevented Serious Injuries	74	9	37		Number of Prevented Serious Injuries	163	55	100
	Number of Saved Lives	7	1	2		Number of Saved Lives	19	3	6
	Value of Prevented (Statistical) Fatality £	29m	3m	12m		Value of Prevented (Statistical) Fatality £	69m	18m	32m

Table 2.11 Safety Benefits Related Extrapolation of Use Cases

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[22] UK Department for Transport. (2017). Reported road casualties in Great Britain: 2017 annual report.

[24] UK Department for Transport. (2013). A valuation of road accidents and casualties in Great Britain: Methodology note.

[25] Social Value UK. (2016). Valuation of a Life.

[26] Waddington, Ian & Thomas, Philip. (2016). What is the value of life?

[27] Thomas P. (2018). Calculating the value of human life: safety decisions that can be trusted. Policy Bristol. University of Bristol.

3. Cost Calculation of the UK CITE

3.1 Introduction

Effective project management ensures that expected project benefits are delivered within the cost, time and quality constraints and within any resource limitations. Economic viability must be taken into consideration as a prerequisite[28]. Using the UK CITE costs as a basis, here we consider the costs of implementing an Intelligent Transportation System (ITS) on UK roads.

3.2 Cost Calculation for ITS

Following existing methodology for transportation projects[28,29], the cost analysis has been conducted in two parts:

- Capital expenditure (CAPEX), including all initial infrastructure-related costs.
- Operating expenses (OPEX), covering the costs that occur throughout the utilisation of the project and its ongoing maintenance.

3.2.1 Capital Expenditure Calculation (CAPEX)

In order to calculate the CAPEX cost of the project, two sets of costs were used: Direct Costs and Backhaul Costs[30]. Direct costs are the capital reserved for the purchase of hardware and its installation. Backhaul costs, on the other hand, are for indirect activities which support such an installation, for example; Planning, Design, Inspection, Traffic Management, Social Impacts and some other similar costs can be included in this category[29, 30]. However, it should be noted that all such costs are context-dependent, and customisation is required in line with the dynamics of projects. Table 4.1 provides the list of potential points to be regarded when the capital expenditure of a project is calculated:

DIRECT COSTS	BACKHAUL (INDIRECT) COSTS
Purchase of the Hardware	Planning and Design
• Technology Hardware	Traffic Management
• Additional Hardware (Pole, Antenna, Cabinet)	Inspection
• Radio Frequency Spectrum Resource	Social Costs
• Power and Communications Cables	
Installation	
• Hardware Installation	
• Power and Communications Installation	

Table 3. 1 Cost items for CAPEX[1,28,31,32,33]

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[1] Tomecki, A.B., Yushenko, K. and Ashford., A. (2016). Considering a cost–benefit analysis framework for intelligent transport systems.

[28] Schulz, W., Geis, I. (2014). Future role of cost–benefit analysis in intelligent transport system-research. IET Intelligent Transport Systems.

[29] Čiapas, A., Rinkevičius, D. (2014). Time is literally money: a cost and benefit analysis of intelligent transportation system projects in Vilnius employing value of travel time estimation.

[30] Texas A&M Transportation Institute. (2018). Connected Vehicle Infrastructure: Deployment and Funding Overview.

[31] Bösch, P. M., Becker, F., Becker, H., & Axhausen, K. W. (2018). Cost-based analysis of autonomous mobility services. Transport Policy, 64, 76-91.

[32] Litman, T. (2015). Autonomous vehicle implementation predictions: Implications for transport planning (No. 15-3326).

[33] Stevens, A. (2001). UK Perspective on Cost-Benefit Assessment of Intelligent Transport Systems. In ITS world Congress in Sydney.

Utilising these points, the cost of a single unit of infrastructure, and hence different system configuration costs and metrics, can be calculated:

Infrastructure Unit Cost x Infrastructure Unit Quantity = Total Infrastructure Cost

Cost per Year = Total Infrastructure Cost / Depreciation Lifecycle of Infrastructure

Cost per Mile = Total Infrastructure Cost / Measurement Area

3.2.2 Operational Expenditure Calculation (OPEX)

Operational expenditure is non-capital cost which will occur along the utilisation of the project. These types of costs can be either one-off or repetitive, varying by the type of contracts. The following cost items have been identified in previous work[33] as relevant to ITS installation:

- Periodical Infrastructure Site Rent
- Periodical Power Consumption
- Periodical Radio Frequency Subscription
- Periodical Cost of Connection to the Core Network
- Maintenance Costs (Physical or Connection)
- Overhead Costs
    - Salary (administration, IT, technicians, installers, drivers etc.)
    - Rent of offices, cabinets, garages
    - Special machinery, cars
    - Maintenance (including spare parts and consumables)
    - Taxes and other expenses

3.3 Approach

This report measures the costs and benefits of different technologies used in UK CITE. Originally these were due to be DSRC (Dedicated Short Range Communication), Wi-Fi, and LTE-V (Long Term Evolution-Vehicle). However, due to the inefficiency of Wi-Fi and insufficient maturity of LTE-V, DSRC was the only technology widely deployed and tested across the project. Hence this cost-benefit analysis is based on this technology.

Initially, world-wide best practice was researched, and different aspects of cost calculation collated as in the previous section (3.2). This has supported the comprehensive identification of all potential issues, some of which have been omitted due to irrelevancy to this project. To compare the applicability of each of the cost items, interviews were conducted with the following project partners: Highways England for motorways; Coventry City Council for urban roads; and Siemens for DSRC technology. This process validated related cost items while excluding those that were either out of scope of the UK CITE project or not applicable to the context. Consequently, the following decisions were reached:

- Due to the lack of deployment of WiFi or LTE-V in the project, the nature of this report has altered from comparing the three technologies to analysing the cost and benefit balance of DSRC technology deployment.
- For both traffic environments, costs related to Radio Frequency Resource or Spectrum are not applicable to the project.
- Social costs, which occur with the impacts of infrastructure installation to public life, could not be reached in both environments due to lack of accessible data.
- Overhead costs have been omitted due to the number of assumptions required. Although organisations have spent on this cost item, it encompasses various departments and projects and has proved difficult to accurately identify the share of this project against the total expenditure.

3.4 Costs of ITS Adoption

Using collected data from consortium partners, the two cost perspectives of CAPEX and OPEX have been combined to calculate the full cost of the project.

Starting with CAPEX, the UK CITE project comprises two main groups of technology infrastructure: road-side units (RSU) and on-board-units (OBU). RSUs enable connectivity along the target environment. They may provide a seamless flow of information along the road by getting information from transmitter vehicles to those that should receive the message. They also convey all the data transmitted along the roads to the central cloud service where more holistic and strategic information sets are created by cumulating data coming from multiple RSUs. In this system of connections, OBUs provide direct communication between vehicles and also become a receptor for datasets sent by either relaying RSUs or the central cloud. In this project, only the costs of RSUs have been taken into consideration and OBU costs excluded. At a much lower cost relative to RSUs, this item was installed in very low numbers, making the cost contribution negligible at this stage.

In addition to the direct cost of hardware, variations in the cost of RSU installation, such as power infrastructure, additional physical infrastructure etc. have been observed in terms of road types, and their characteristics have determined the major cost differences between them. On motorways, CAPEX is double that of urban, caused in the main by the additional infrastructure requirements of the motorway environment. In this situation, RSUs' technology (DSRC) hardware is needed to deploy to a pole within a cabinet and with an antenna at the top of the pole, increasing the cost of installation. Additional costs include provision and connection of the power and communication cables, and management of the traffic during installation. However, in urban roads, there are various technology hubs already in place throughout the city, and instead of bringing new physical infrastructure to the environment, the DSRC hardware is installed directly on the existing infrastructure. Power and communication cables are more plentiful and available, easing the installation of the hardware, and the process can often be completed without disturbing the normal flow of traffic, hence decreasing the total cost of RSU deployment in the urban environment compared to that of the motorway.

By collating the required data from local authorities (Highways England for motorways and Coventry City Council for urban roads), the cost of a single RSU unit has been calculated respectively as £116,892 and £10,300. Within the UK CITE project, 35 RSUs have been installed along 40 miles of motorway and 21 on 6 miles of urban road. These figures give the total CAPEX per environment, which are £4,091,220 and £216,030. Further, the "cost per mile" for each road type is £102,281 and £36,050 for motorway and urban, respectively. Considering lifetime depreciation, DSRC hardware is considered to have a useful lifetime of an average of 5 years before requiring some form of upgrade. Accordingly, the annual cost per mile of CAPEX for the first 5 years of technology deployment then becomes respectively £20,456 and £7,210 (see Table 3.2).

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[33] Stevens, A. (2001). UK Perspective on Cost-Benefit Assessment of Intelligent Transport Systems. In ITS world Congress in Sydney.

	MOTORWAY	URBAN
RSU Unit Cost	£116,892	£10,300
Used RSU	35	21
TOTAL CAPEX	£4,091,220	£216,030
Project Range	40 miles	6 miles
Cost per Mile CAPEX	£102,281	£36,050
Technology Depreciation Time	5 years	5 years
Annual Cost per Mile CAPEX (for the first 5 years)	£20,456	£7,210

Table 3.2 CAPEX calculation for motorway and urban environment

Considering OPEX, costs about annual power consumption, connection to the core network, and maintenance (both physical and connection-related) were collected from Highways England and Coventry City Council. With this, annual operating expenditure for both road types has been calculated: £1,129,650 for motorways and £355,796 for urban roads. Given these costs over 40 miles of motorway and 6 miles of urban, the "operating cost per mile" can be calculated at £28,241 and £59,299 per annum respectively.

A holistic cost framework, then, is as seen in the following table:

	MOTORWAY	URBAN
TOTAL CAPEX (per mile)	£102,281	£36,050
Depreciation Time	5 years	5 years
CAPEX (per mile per year)	£20,456	£7,210
OPEX (per mile per year)	£28,241	£59,299

Table 3.3 Cost per mile analysis for motorway and urban environment

When considering costs in a per year framework as in Table 3.3, CAPEX of motorway triples that of urban roads. On the other hand, in OPEX, the cost of urban outweighs motorways by a factor of two. The frequency of RSU placement greatly contributes to this disparity. DSRC technology is based on "line-of-sight" principle and RSUs are expected to see each other. Because of the environmental differences, while the average distance between two RSUs on motorway is 1.3 miles, it is only 0.3 miles in the urban part of the UK CITE project. The improvements in DSRC technology and its collaboration with other technologies may increase the effective range between RSUs, and hence future ITS implementations may require less infrastructure, and hence less cost.

3.5 Extrapolation

Connected and automated technologies are gradually developing with increasing interest from the public, governments and industry. In the context of UK CITE, we have investigated the costs of implementing DSRC technology into two road environments: motorway and urban. By extrapolating the findings and increasing to full UK scale, we may demonstrate future potential costs and compare to expected benefits.

In order to scale effectively, the characteristics of road types within UK CITE should be noted. The motorway environment is a typical example of, and directly represents, the UK motorway network. Therefore, cost extrapolation of this road type has been applied to the full 2,300 miles of motorway roads. On the other hand, UK urban roads have mainly two types: urban "A" roads, and minor roads. In the UK CITE context, the term 'urban' mainly represents the urban "A" roads of the UK traffic environment. Hence, they are extrapolated to 6,867 miles of urban "A" roads across the UK. The following table demonstrates the extrapolated costs of adopting CAV technologies (specifically DSRC) across the UK:

	MOTORWAY (2,300 miles)	**URBAN** "A" ROADS (6,867 MILES)
TOTAL CAPEX (per mile)	£235m	£248m
Depreciation Time	5 years	5 years
CAPEX (per mile per year)	£47m	£50m
OPEX (per mile per year)	£65m	£407m

Table 3.4 Cost extrapolation for motorway and urban environment

4. Cost-Benefit Analysis

The previous two chapters of this report have provided detailed explanations of the benefits of some CAV technology adoptions and for the costs of enabling them. These two perspectives are combined in Table 4.1 to provide the fundamental monetary comparison of the costs and benefits of CAV technology applications used in UK CITE.

	MOTORWAY (2,300 miles)		**URBAN** (6,867 miles)	
TOTAL CAPEX	£235m		£248m	
OPEX (per year)	£65m		£407m	
BENEFITS	£17m	£54m	£27m	£55m

Table 4.1 Monetised comparison of costs and benefits of CAV adoption across UK road network

It is critical to note the nature of this cost-benefit consideration, namely cost effectiveness analysis, given the lack of monetary equivalent for many of the performance indicators. A purely financial analysis, as in Table 4.1, illustrates that the costs of implementing ITS infrastructure at current prices considerably outweighs the expected annual benefits for both road environments. It is clear that with the assumptions used to generate these figures there is no point at which the benefits will balance the costs incurred.

However, this evaluation does not take into account the impacts without a quantified financial dimension such as improved air quality and population health, which have not been monetised here. Mobility benefits and improved quality of life for less independent or more vulnerable members of society may produce both financial and less tangible benefits, as would other environmental benefits. All of these elements may affect the population and public services and produce benefits which, in further work, it may be possible to incorporate into this analysis more explicitly.

The simulations undertaken as part of the UK CITE project envisage that up to 313 serious injuries can be avoided and 28 lives saved. This important safety aspect has been monetised, but further savings from other aspects may also be possible. It is also reasonable to assume that as the technologies mature and become more widely adopted, the associated costs will lower, reducing the divide between the costs and benefits still further.

* Monetised figures of benefits are composed of the total of benefits coming from all four use cases of this research. These results assume that all the impacts are measured separately. Considering these applications will be simultaneously used in real life, they may impact on the same event, which decreases the total impact number. Therefore, measured impacts in the table have been accepted as the maximum possible outcome.

5. Conclusion and Recommendations

In this report, we have provided a comprehensive perspective from the UK Connected and Intelligent Traffic Environment (UK CITE) project by bringing its costs and benefits together. Going beyond project-specific parameters, we have discovered some potential opportunities and expected costs to realise them, touching on various performance indicators. We have validated that the most noticeable gain will be in the safety of the roads, reflected in our daily lives by a significant reduction in accidents and the severity of those accidents, leading to more lives saved and fewer injuries. Considering expenditure, we have displayed that even though it is costly to install the infrastructure in motorways, the environmental conditions may require the use of more RSUs in urban roads, creating a higher operating cost and hence creating more balance across these two environments.

Despite limitations on both perspectives of the study, the following inferences could be made:

- Urban roads will become safer as the penetration level of CAV technology increases. Although the nature of this study could not enable us to gather statistically significant results for the motorway environment, we may expect similar impacts in motorways and encourage researchers to conduct motorway-specialised studies to reveal that potential.
- Up to 28 lives will be saved, and 318 serious injuries will be prevented each year leading to £118 million in annual costs savings.
- The deployment of DSRC technology per mile will cost approximately three times less in urban roads than in motorways, while the operating costs in urban will outweigh that of motorways by a similar factor due to the technological environmental requirements. However, developments in communication technologies (e.g. LTE, 5G) may resolve the need for infrastructure, so that much of the capital expenditure may reduce substantially.
- GHG emission reduction from just the warning mechanisms extends the discussion of CAV technological capabilities for a sustainable future.

Future studies may discover more benefits that will be gained with ITS adoption on UK roads. Recommendations for future research are as follows:

1. Crash Type: This study focused on rear crashes due to the availability of simulation and measurement data. Considering front or side crashes may reduce the number of accidents or their severity further, increasing the available benefits.

2. Involved Parties: Our study has focused on only car occupants which comprise nearly half of the accidents in the UK. However, pedestrians, pedal cyclists and motorcyclists constitute the majority of the fatalities and injuries. Illuminating the effects on these parties will give more information about the potential impacts of CAV technologies.

3. Vehicle Type: To provide our internal validity, we have used only cars in our experiments. Together with the increasing amount of test capabilities and resources, all types of vehicles can be involved in future trials to observe their impact on all types of benefit categories. For example, as cars and trucks have separate speed and access limits, they will have different influences concerning mobility. Likewise, these two vehicle categories, like all others, have varying rates of fuel consumption and GHG emissions. Widening the types of vehicles considered in the studies will produce more accurate results better representing real life scenarios.

4. Cooperative Measurement: In this study, we have examined the individual impacts of four use cases within the scope of the UK CITE project. Together with the developing capabilities, benefits should be observed holistically to research individual CAV applications' potential synergetic or antagonistic impacts on different benefit categories and performance indicators. CAV applications could be combined within the experiments and measured concurrently to get closer to reality, as, in real life, all these technologies will be utilised cooperatively.

5. Measurement Method: Since CAV technologies are at their infancy, it is hard to measure their real impacts on the roads. Different attempts were used to conduct road trials within the project, however the focus was on the technicality of the technologies. To gain insight about the future influences of CAVs on our lives, we need to process more data, and for now, it becomes available by simulation in most instances. However, simulations have their own limitations such as being a controlled environment and not allowing detection of an unexpected, new situation that might occur in real life. With developments in simulation technologies, measurement can be enhanced and field experiments can provide validation and the detection of real impacts.

6. Use Case Taxonomy: In this report, we have illuminated the impacts of four CAV applications in the context of the UK CITE project. However, there are various other applications in the field, often with different labels or slightly different functionality. There is a need for a taxonomical study to help better analyse both the expected and unanticipated impacts of CAV adoption with a more systematic approach. Moreover, a taxonomy is required to categorise use cases according to their targets. While some use cases like Emergency Vehicle Warning are more informational, others such as Emergency Electronic Brake Light aim to warn drivers for an urgent behaviour. Such a taxonomy will help us understand each use case's importance.

7. Road Types: Our report has investigated the impacts of CAV technologies on motorways and urban "A" roads. However, these road types comprise less than half of the road network of the UK, leaving minor urban roads and rural roads. Future studies should identify the strategies to take CAV technologies across all road environments, and their associated costs and benefits.

8. Cellular Technology: Since the the installation and operation of traditional roadside units are responsible for the majority of the cost, technologies that require less physical infrastructural design, such as cellular network, may significantly alter the cost level and profile.

9. Developments in DSRC: The cost calculation is directly affected by the range and distribution of RSUs along the road network. With improvements in the technology of DSRC, it may have better communication capabilities which may decrease the required number of units. The efficiency of RSUs could also be observed in a longitudinal study. Different configurations, such as leaving RSUs only in critical locations (such as junctions) may provide a more cost-efficient RSU network.

Appendix

Formulas of "Vehicle Performance Based Effectiveness" Performance Indicator[9]

TTC (Time to Collision)

The difference among different penetration levels can be clarified by *crash avoidance effectiveness*, which is derived by comparing near-crash rates P for vehicles with and without the CV technologies, as shown in the following formula:

$$Effectiveness = 1 - \frac{P_{with}}{P_{without}}$$

Where,

$$P = \frac{No.of\ TTC < Threshold\ TTC}{Total\ number\ of\ recorded\ TTC}$$

TET (Time Exposed TTC)

The superscript * should be interpreted as 'indicator value calculated with respect to the threshold value':

$$TET_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{SC}$$

$$\delta_i(t) = \begin{cases} 0, & else \\ 1, & \forall 0 \le TTC_i(t) \le TTC^* \end{cases}$$

For a population of N drivers (i=1 … N), it is easily understood that the total TET* is equal to:

$$TET^* = \sum_{i=1}^{N} TET_i^*$$

TIT (Time Integrated TTC)

In continuous time:

$$TIT^* = \sum_{i=1}^{N} \int_0^T [TTC^* - TTC_i(t)]dt \qquad \forall 0 \le TTC_i(t) \le TTC^*$$

The individual TIT for subject i in discrete time can be calculated with:

$$TIT^* = \sum_{i=0}^{N} [TTC^* - TTC_i(t)] \cdot \tau_{sc} \qquad \forall 0 \le TTC_i(t) \le TTC^*$$

The following discrete-time aggregate TIT definition (expressed in s2) is a result of the summation over all vehicles (i=1….N) present in the investigation during time period H.

$$TIT^* = \sum_{t=1}^{N} TIT_i^*$$

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[9] Minderhoud, M.M. and Bovy, P.H. (2001). Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention, 33(1), pp.89-97.

Unsafety Index

$$U = \Delta S \cdot S \cdot R_d \quad [m^2/s^2]$$

Where;

U : unsafety parameter [m2/s2]

ΔS : speed difference between two vehicles at collision time [m/s]

S : speed of the follower's vehicle at collision time [m/s]

R: ratio between the deceleration of the leader vehicle and its maximum deceleration capacity

To have a global vision of the network in terms of the Unsafety Density;

Where;

$$UD = \frac{\sum_{s=1}^{S_t} \sum_{v=1}^{V_t} U_{V,S} \cdot d}{T \cdot L} \qquad [m/s^2]$$

UD : unsafety density [m/s2]

Uv,s : unsafety of vehicle v in simulation step s [m2/s2]

Vt : number of vehicles in the link [-]

St : number of simulation steps within aggregation period [-]

d : simulation step duration [s]

T : aggregation period duration [s]

L : section length [m]

Shaping the future

Intelligent Vehicles Group

Intelligent vehicles (IV) are set to transform the UK economy and WMG are recognised as a centre of excellence for connected and autonomous vehicle research. Our multidisciplinary approach, including cooperative driving systems, connectivity, human factors and verification and validation, enables a full understanding of the practical applications that will help shape the future of transport mobility.

Principal Investigator: Professor Paul Jennings

Supply Chain Research Group

WMG's supply chain research group (SCRG) apply customer responsive supply chain theory into practical solutions that generate both economic and societal value. Collaborating with industrial partners, the SCRG seek to resolve complex business and organisational problems across agrochemicals, automotive, defence, consumer-packaged goods, retail and pharmaceuticals.

As a society aspiring to become more responsible consumers, we try to use less, use more sustainably and more ethically. In the automotive industry this is leading to the development of technologies that support low emissions mobility that is connected and autonomous. The supply chains for these new technologies do not currently exist. SCRG are developing methodologies to identify the market opportunities and design new sustainable supply chains for emerging technologies. Along with the transition to the next stage of industrial revolution, we have developed approaches to explore new business models that are supported by design in supply chains to deliver complex value propositions.

Principal Investigator: Professor Janet Godsell

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