A Case-based Cost-benefit Consideration for Upgrading to an Intelligent Traffic Environment

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Abstract

Within the trend of transforming our daily lives into a smart form, traffic has become one of the development areas for innovators and hence researchers. While many technologies are devised or improved for Intelligent Transportation Systems (ITS), potential impacts of ITS have also raised the interest of researchers. In line with this trend, this study conducted case-based research to identify the potential benefits of ITS implementation in the UK traffic network and to analyse its applicability from a cost-effectiveness perspective. In our analysis, we have utilised four use cases in two different road environments –urban and motorway- and analysed their efficiency in three traffic density levels. Our findings demonstrate some specific benefits like the improvement in the safety of urban roads even from the lowest level of technology penetration and also fixed and incurring costs. However, having an immature and continuously developing nature, the field requires more interest and work from researchers in many aspects to obtain further inference about potential benefits and preventable costs.

1 Introduction

Intelligent Traffic Systems (ITS) is a trending subject of research and innovation as being one aspect of creating smart cities. Following this trend, we analysed the applicability of the idea in the UK traffic network with a cost-benefit analysis point of view.

Analysing the relationship between anticipated cost and expected benefits is a frequently adopted method to determine whether the project's benefits exceed the corresponding costs. Ideally, decision-makers aim to assess the applicability of a project by quantifying -generally monetising- the benefits and costs, and then calculating the potential net consequence to gather at the end. However, the measurement is generally bounded to the availability of the information. When monetary values are available only for costs, an approach called Cost-Effectiveness Analysis is applied. If monetary values are not available at all, on the other hand, Multi-Criteria Analysis is recommended.

This report's cost-benefit relationship consideration is based on the second approach: Cost-Effectiveness Analysis, because of the difficulty of determining monetary impacts of the benefits at this stage. Although each benefit indicator can be statistically monetised in various means, it is not suitable to constrain the benefits of ITS implementation to a simple economic consideration as they also mean many social improvements such as saved lives, decreased injuries, safer roads, better travel experiences or greener environment [1].

To investigate the beneficial impacts and potential costs in detail, this study adopts a case-based approach. It is based on a UK government-funded project – UKCITE (United Kingdom Connected and Intelligent Traffic Environment)- which analyses potential communication technologies in the traffic and evaluates their functionality and impacts in many aspects like technology maturity, cybersecurity, testing methodologies, and wider economic and societal implications. This study comprises the part where measurable benefits and costs of the project were comparatively assessed. More specifically, it aims to identify the aspects and wider framework of benefits coming with the adoption of Connected and Autonomous Vehicle (CAV) -or Connected vehicle and driving assistance (CV&DA) in other saying- technologies; to anticipate the implementation and operation costs of these technologies; and to scale foreseen benefits and costs this transformation to the total of UK road network.

To fulfil these objectives, the paper will first introduce the potential benefits expected from a transition to an intelligent traffic environment and its corresponding cost in Section 2; then, elaborate its methodological process in Section 3; present the findings in Section 4 and lastly further discussions and inferences in Section 5.

2 Literature Review

2.1 Benefits of Creating an ITS

The earlier research in Intelligent Traffic Systems (ITS) has defined four main types of corresponding benefits: mobility improvement, environmental uplift and enhanced safety status and economic benefits [2]–[5]. This research, however, accepts the economic benefits as the result of the other benefit dimensions and focuses only on these three to identify the evolutionary impacts of connected and autonomous technologies on traffic.

2.1.1 Safety benefits: Human-led faults have an important

place among the causes of traffic accidents. Evidence 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 [6]. Advancements in CAV technologies bring an opportunity to mitigate the adverse effects of human nature.

To examine the effectiveness of the CAV technologies regarding safety improvements, the literature harbours two categories of measurement: crash-avoidance-based effectiveness and vehicle-performance-improvement-based effectiveness. The former considers the number of conflicts and near-crash events in a real-world environment and sets forth the crash reduction effectiveness by using parameters like 'Time-to-Collision (TTC) and Crash Avoidance Effectiveness', 'Time Exposed TTC (TET)', 'Time Integrated (TIT)' and 'Unsafety Index'. The latter, on the other hand, is mainly used in simulation-based studies where the real-life impacts of CAV technologies like crash incident reduction cannot be measured yet. The parameters used in this aspect are 'Change in Average Conflict Number' and 'Change in Average Number of Fatalities and Injuries'.

Time-to-Collision (TTC) and Crash Avoidance Effectiveness: TTC is defined as the time left for a potential collision between two same-direction vehicles after the car behind starts breaking (Figure 1). In other words, a low TTC value means a higher risk of accident and while a high TTC value means a lower risk of an accident [7]. When the TTC value is less than a threshold, it is accepted that the vehicles are in a conflict or an unavoidable collision path. This threshold value is suggested to be 1.5 seconds according to the minimum perception and reaction time of a driver [8], [9].

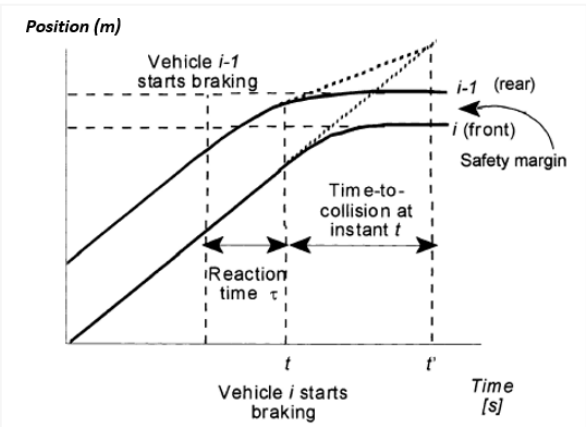

Figure 1 Time-to-collision notions illustrated with vehicle trajectories [9]

Although a single TTC indicator is not to draw any meaningful inference, considering all the simulated traffic environments, we produce an incident probability figure by proportioning the total number of cases having the TTC_{test} below $TTC_{threshold}$ to the total case number (all breaking moments) (Formula 1) [10]. Further to that, to have comparative analysis among different penetration levels or time series we can also utilise crash avoidance effectiveness, which is produced by comparing near-crash rates for vehicles with and without the CV technologies (Formula 2) [12]:

$$P = \frac{No.of\ TTC < Threshold\ TTC}{Total\ number\ of\ recorder\ TTC} \quad (1)$$

$$Crash\ Avoidance\ Effectiveness = 1 - \frac{P_{with}}{P_{without}} \quad (2)$$

Time Exposed TTC (TET): It refers to the cumulative length of time that vehicles are below the threshold value of TTC [9]. Hence, the lower the TET, the less time the vehicles are in the risk of conflict and so the safer the situation is [7].

Time Integrated TTC (TIT): Although TET improves the standard TTC by bringing an additional level of detail, it still has its disadvantage of being incapable of measuring the strength of below-threshold TTCs. For instance, it cannot differ the risk of two situations where both stayed 2 seconds below the threshold TTC, where the situations have 0.1 and 1.4 average TTC respectively. Apparently, the first case (0.1) is more dangerous than the other. On this kind of occasion, we can utilise Time Integrated TTC (TIT) to include the risk weight of TTC cases [7].

Unsafety Index: This indicator harnesses more parameters like the position, speed and maximum breaking capacity of the two following cars. When the unsafe parameter is zero, it means the cars will not crash. To apply it to the environment level, we apply the unsafe density parameter. This parameter also enables us to compare the safety level among different networks or time series [9].

Crash avoidance-based effectiveness: Unlike the other, the crash avoidance-based effectiveness utilises real-life data like average conflict number and the average number of fatalities and injuries to measure the effectiveness of adopted CAV technology. Although it gives more realistic results than simulation-based methods, it also has drawback related to the difficulty of data collection. Especially for novel technologies that are in the test phase, simulation data is used to predict their potential impacts [4], [12].

2.1.2 Mobility benefits: Besides bringing safety enhancements, CAV technologies also facilitate the mobility of the citizens. Traffic congestion is accepted as the main cause of mobility inefficiencies and the corresponding costs due to various reasons like time waste and fuel consumption [11]. To create solutions for these problems, CAV technologies are considered as the potential means by creating interactive traffic networks that can predict potential jams and suggest alternative efficient routes.

Literature harbours two interrelated indicators to measure mobility enhancements. First is the improvement in the travel time. Through real-time guidance and rerouting functions,

assisting technologies can provide real-time information about disruptive situations like traffic incidents, lane closures or construction zones to drivers and increase their decision-making abilities to reduce their time spent in the traffic [5], [13], [14]. The other perspective is, on the other hand, is to measure the mobility improvement by the increase in the average speed of the traffic [4], [15].

2.1.3 Environmental Benefits: The last benefit aspect from CAV technologies refers to the environmental benefits. Transportation is accepted as one of the largest contributors to air pollution and greenhouse gas emissions. Among these most significant pollutants, there are carbon monoxide (CO), carbon dioxide (CO2), volatile organic compounds (VOCs) or hydrocarbons (HC), nitrogen oxide (NOx) and particulate matter (PM) and these pollutants possess serious threats for human health and environment.

For decreasing these human-led harms, some initiatives directly target the issue, like changing the fuel type to electric. However, a system-wide improvement is also required for further mitigations and CAV technologies play their parts there. They are expected to contribute to emission reduction while it brings solutions for traffic congestion. While CAV-provided additional network information assists the drivers in their travel, the related change in driver behaviour results in fewer accelerations and decelerations, which are substantially important for emissions. These variations in the usage of the vehicles also impact fuel consumption, which also utilised as an indicator of the environmental benefits [4], [16], [17].

2.2 Cost Calculation for ITS

Projects are planned to achieve the desired objectives and at the same time, they consider the limitations of available or allocated resources like time, capability, capacity, and cost. The cost or the economic viability of a project must be taken into consideration as a prerequisite [18]. The cost of transportation projects is commonly calculated in two classes. First is the capital expenditure (CAPEX) which includes all initial infrastructure-related costs and the second is operating expenses (OPEX), covering the costs that occur throughout the utilisation of the project and its ongoing maintenance.

2.2.1 Capital expenditure calculation (CAPEX): Capital expenditures of a project are analysed in two parts: Direct Costs and Backhaul Costs (Texas A&M Transportation Institute 2018). Direct costs are the capital reserved for the purchase of hardware and its installation. Its coverage goes beyond the sole main technology and includes supportive equipment like pole, cabinet, antenna, power and communications cables and infrastructure like radio frequency spectrum resource. On the other hand, backhaul costs are for indirect supportive activities such as planning, design, inspection, traffic management or social impact costs [19], [20]. However, cost calculation is a context-dependent process that requires adequate customisation.

Though we can utilise the simple calculation, we can go beyond that by analysing periodical or spatial costs of the project, applying the following formula:

$$TC_I = UC_I \times Q_I$$
$$AC_I = TC_I / DT$$
$$MC_I = TC_I / MA$$

where TCI is total infrastructure cost, UCI is infrastructure unit cost, QI is the required infrastructure quantity, ACI is annual infrastructure cost, DT is depreciation lifecycle of infrastructure, MCI is mileage cost (cost per mile) and lastly MA is measurement area.

2.2.2 Operational expenditure calculation (OPEX): Capital expenditures prepare the infrastructural base of the project; however, a viable project plan should include the required consideration for the operational processes throughout the project. Costs related to operations can be either one-off or repetitive. Based on that idea, [21] mainly defines two types of operational costs. First is periodical costs which include infrastructure site rent, power consumption cost, radiofrequency subscription, network connection, maintenance costs (physical or connection). The second is the overhead costs that cover the salary (administration, IT, technicians, installers, drivers, etc.), rent of facilities (e.g. offices, cabinets, garages), special equipment or vehicle rental, maintenance equipment (including spare parts and consumables) and taxes and other expenses.

2.2.3 Contextual Complexities of Cost and Benefit Identification: Involving numerous variations of scenarios and parties, traffic is a complex concept. In any improvement plan, for reaching the best result, implementers ideally should consider all these variations. Yet, the job itself has some inherent difficulties, such as data unavailability or lack of measurement capability. Hence, it requires making some assumptions for the unknown variables and drawing as much meaningful inference as possible with the available resources.

The first complexity occurs by the variety of vehicle types in the traffic. When different vehicle types are examined, the benefits and costs may vary, for example comparing fuel consumption between trucks and cars. This is evident in the case of another prominent example, namely speed limit differences among vehicle types. Therefore, without addressing the vehicle type contingencies, we cannot produce a considerable project and insight.

Another essential complexity aspect is the types of crashes. CAV technologies are distinctively designed for different crash types. Crash types may differ according to its involving parties (i.e., car-car, car-pedestrian, car-cyclist, etc.). The tested technologies should be examined in situations where they have been initially aimed for [5].

A change comes always with some expected contributions. However, it may be more difficult than presumed when we go beyond analysing a single benefit to examining the interrelationships among all benefits and costs. They may show synergetic nature, for instance, GHG emissions are a result of congestion, and any CAV technology-led decrease in congestion will also be reflected as a reduction in GHG emissions. On the other hand, they may have an antagonistic relationship, where a benefit dimension has an adverse impact on the other. For example, when the rerouting assistive technology is expected to increase the average speed, it may, at the same time, result in higher emissions and fuel consumption [4].

A similar holistic approach is also required for the interrelationships of the technologies [22]. Previous studies report two aspects to analyse these relationships: the relational effect and the combined effect [4], [22]. The former compares the separate results of corresponding benefit types, while the other is based on the fact that all CAV technologies are parts of a holistic project and will be used simultaneously. Therefore, it asserts that testing the cooperation of these technologies can bring more realistic inferences.

3 Methodology

To have the required deeper insight into both the benefits and costs perspectives, a case study approach is adopted for this study. [23] defines the case study as the investigation of a contemporary phenomenon within its real-life context, especially when the boundary between phenomenon and context is fuzzy. As the ITS is a contemporary phenomenon and needs clarification to determine its implementation framework in different aspects of real-life context.

The case of this study is based on a UK government-funded multi-organisation project, namely UK Connected and Intelligent Traffic Environment (UKCITE), that investigated the adaptability of some potential CAV technologies into ITS and assessed the functionality, safety, and convenience of connected and autonomous vehicles. As a versatile project, it evaluated the implementation of these technologies from many aspects like technology maturity and cybersecurity. In coordination with these, the part of the project belonging to this study illuminated the benefits of converting the UK's established road network into a Connected and Intelligent Transportation Environment and the costs of this transformation.

The empirical side of this study has been conducted in four steps. First, academic and grey literature have been reviewed to define the state of the field. However, as mentioned before, ITS are versatile projects and require to be embedded in the context. Therefore, to produce a tailored cost-benefit analysis for the case, in the second phase, the stakeholders whose expertise varies by the different aspects of the projects were consulted via a questionnaire about the costs and benefits that apply to the project. Utilising the initial questionnaire results, we created a draft framework and in the third phase, stakeholders were consulted on the viability of this framework in a subsequent web-based panel. The consultation phase was reinforced by another run of the panel, which this time only included specific stakeholders who owned the required data for the measurements. At the end of the consultation process, we concluded with a final framework which has included two primary indicators for each benefit dimension, four use cases that the technologies will be adopted, the traffic level specifications of the analysis, the communication technology that will be utilised for cost analysis and the required cost items. In the last phase, the required data were collected by two simultaneous activities, which are simulation modelling of traffic via the VISSIM simulation tool and the collection of secondary data from the required stakeholders.

4 Results

4.1 Benefits of UKCITE

As a result of the cohort consultation phase, two primary indicators for each benefit category were selected to measure the impacts of the adopted CAV technologies. At the same time, we also decided on the level of analysis for factors like technology penetration levels, road environments, traffic density and the use cases to be concentrated in the study. They were mainly identified by the requirements of the project although they were occasionally constrained by the context-related and case-specific practical complexities. In practical terms, the biggest issue was the availability of real-life data. As mentioned, for the innovative technologies, it is not possible to use real data as they are in the development process. However, we aimed to have a real-life match of simulation benchmark to analyse the improvement in the targeted perspectives. However, due to the scarcity or lack of real-life data, the analysis could only be benchmarked to the base level of simulation, which refers to the situation where nearly no technology is applied. Besides, we also had simulation-related constraints. While we aimed to make inferences about the fatalities and injuries, the used simulation (VISSIM) could not produce these indicators, and we could only measure the reduction of average crashes. Consequently, we conducted our analysis with the indicators shown in Table 1 and the traffic attributes in Table 2.

Table 1 Primary performance indicators for each benefit category

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 Traffic attributes analysed through simulation

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%)

From this point on, the results related to benefits will be presented by their impacts on the four use cases.

Emergency Electronic Brake Lights: This use case primarily aims to bring safety improvements by informing the driver about suddenly occurring incidents and providing them extra reaction time. In this case, the occasion is that the front vehicle unexpectedly reduces its speed or stop.

As expected, in both road environments, the safety benefits were observed by the selected safety indicators. The improvement for both indicators was observed from the lowest technology penetration level. Additionally, in the urban environment, the use case resulted in a reduction in CO emissions, as it decreases the requirements for sudden braking. All the benefits achieved were observed in a trend that correspondingly increases with the penetration level. In other words, as the CAV technologies that enable the EEBL use case to become more prevalent in the traffic, their benefits will be correspondingly increased.

Emergency Vehicle Warning (EVW): The purpose of this use case is to provide emergency vehicles an uninterrupted journey to reach their destination as earliest as possible. In the application, the vehicle receives the signal either from another vehicle or directly from a roadside transmission unit, which informs an emergency vehicle is approaching from behind. This early signal gives the required time the required preparation time.

As the mainly targeted benefit is not associated with all the vehicles in the traffic but for the emergency vehicles to decrease their travel time, we made our analysis in two adjusted benefit indicators. We observed a decrease in EV travel and delay times in the urban environment in parallel with the rising penetration of technology. We presume that the difference between road types comes from their nature, as the urban environment is more prone to congestion; the more amelioration is achieved there. In another aspect, the improvement ratio can seem minor; however, considering the limitations of the study and the additional societal benefits of the use case, we accept that the observed impact is promising for a newly developing technology.

Traffic Condition Warning (TCW): This use case informs drivers about any incident ahead that can impact the flow of traffic and that drivers are required to arrange their speed accordingly. The example situations are like heavy traffic congestion, the end of a static queue, or slow-moving traffic. Communicating with each other, connected vehicles signal about the current traffic flow and coming drivers are given notice to brake earlier and more progressively. This creates a safer traffic flow by reducing the risk of the inattentiveness of the driver. Despite its similarity to EEBL, TCW is based on an earlier notification system than EEBL. Therefore, besides the safety-related precautions, the use case also aims to bring significant impacts on other benefit categories, such as smoother traffic flow and more stable acceleration behaviour.

In our simulation, the TCW use case showed its highest benefit potential in the safety category in the urban road environment by increasing drivers' awareness of the traffic and their reaction period. However, we achieved this result only for the urban road, as we could not get enough crash amount in the simulation for the motorways to draw meaningful inferences. Besides, we also could not reach our expected improvements for mobility and environmental benefit categories. Conclusively, the TCW use case is either not the best solution for mobility and environmental problems or it requires complementary technologies to reach its best performance. As mentioned in the complexities part, CAV technologies' performance may change in different situations of which one is when they are used in cooperation with other technologies (Yue et al., 2018).

Roadwork Warning (RW): The use case is specifically designed to warn drivers when they approach any roadworks taking place in the traffic, such as a lane closure or a request or temporary speed reduction situations for safety reasons. Similar to TCW's application in the dangerous end-of-queues, this use case aims to reduce the number of conflicts caused by roadworks by using communication technologies of the connected vehicles. It is also expected to bring mobility improvements by leading drivers to the appropriate lane utilisation.

Like the previous use cases, it is hard to get inferences for safety because of the low number of crashes in the motorway environment of the simulation (Table 8). On the other hand, in the urban environment, a highly significant decrease in the number of average conflicts and an important reduction of CO emissions were obtained, while for the mobility-related benefits further research is required which will combine different use cases or use other technologies.

4.1 Costs of ITS Adoption

CAV technologies are based on various combinations of communication technologies. In this project, the comparison of three main technologies (DSRC (Dedicated Short-Range Communication), Wi-Fi, and LTE-V (Long Term Evolution-Vehicle)) has been accepted for the main objective, however, due to the inefficiency of Wi-Fi and immaturity of LTE-V, DSRC became the only technology deployed and tested across the project. So, this cost-benefit analysis is based on this technology.

After collating the best practices of cost calculation (see Section 2.2.2), the applicability of each cost item was identified via interviews that have been done with corresponding project stakeholders. By this process, adopted cost items were validated while others were excluded from the study. For example, interviews identified that costs related to Radiofrequency Resource or Spectrum do not apply to the project for both traffic environments. In addition, due to the data unavailability, social costs -occurring with the infrastructure installation as the side effects on public life- and overhead costs could not be included in the study.

To calculate the full cost of this CAV project, the two cost perspectives of CAPEX and OPEX have been utilised. Regarding the CAPEX, two main groups of technology infrastructure were defined: roadside units (RSU) and on-board-units (OBU). RSUs provide connectivity along with the traffic and enable a seamless information flow among the transmitting and recipient vehicles. Additionally, they also send all these transmitted data to the central cloud data storage service where the datasets are cumulated to create either more holistic operational decisions or strategic-level long-term improvements. OBUs, on the other hand, perform the transmitter and receptor role in the vehicles. As much as they transmit data to the closest RSU, they can also enable vehicle-to-vehicle (V2V) communication, especially for urgent situations. In this study, costs of OBUs were excluded as being at a much lower cost relative to RSUs.

RSU cost may depend on the main technology it involves; however, it can also vary in additional requirements like power infrastructure, additional physical infrastructure or the projected road types. For example, CAPEX for motorways is double that of urban, as it requires additional infrastructure requirements. In the motorways, RSUs' technology hardware (DSRC) is deployed to a pole within a cabinet and with an antenna at the top of the pole. Additionally, motorways require provision and connection of the power and communication cables and the cost of traffic management during installation. The urban environment, on the other side, already harbours various technology hubs throughout the city. Hence, instead of installing new physical infrastructure, the DSRC hardware is attached directly to the existing infrastructure. Likewise, the availability of power and communication lines facilitates the installation and also removes the traffic management cost as it will not impact the normal flow of traffic.

In the light of these initial decisions, we collected the necessary data from corresponding stakeholders. Conclusively, the cost of buying and installing a single RSU unit was determined as £116,892 and £10,300 respectively. Within the project, 35 RSUs have been installed along 40 miles of motorway and 21 on 6 miles of urban road. Therefore, we can produce the CAPEX cost of the project, as in Table 3:

Table 3 CAPEX calculation for motorway and urban environment

	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

Regarding the OPEX costs, necessary data about the annual power consumption, connection to the core network, and maintenance (both physical and connection-related) were collected from the mentioned stakeholders. In conclusion, the following annual operating expenditures have been identified: £1,129,650 for motorways and £355,796 for urban roads. Given these costs are for the overall project (40 miles of motorway and 6 miles of urban), the "annual operating cost per mile" was calculated as £28,241 and £59,299.

When we have a holistic look at both cost perspectives in Table 4, we see that motorway triples urban in CAPEX while in OPEX, the relationship is the opposite where urban's doubles the motorway costs. This reverse relationship comes from the nature of DSRC technology. It is based on the "line-of-sight" principle where RSUs must see each other to communicate. Because of the environmental differences of the two road types, the places of the RSUs and their placement frequency varies. Since the average distance between two RSUs on the motorway is 1.3 miles and only 0.3 miles in the urban, the determined cost differences occur. However, the improvements in DSRC and other communications technologies will increase the effective range of RSUs which makes the ITS implementations of the future less expensive.

Table 4 Cost-per-mile analysis for both road environments

	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

5 Discussions

5.1 Further Opportunities of ITS Adoption

The results obtained in the previous section are within the limits of the project, however, we can analyse the further potential opportunities that can be gained through an intelligent and connected traffic environment. Overall, the investigated use cases decreased the average crash figures on the urban environment by 8%, while the simulation could not produce meaningful results for motorways except for the EEBL use case. Yet, this is not an unusual situation as the annual report of the UK Department for Transport [24] also states that motorways are statistically three times safer than urban roads. According to the same report, only 6% of vehicle fatalities occur in motorways, in comparison to the urban with 32% and the rural roads with 62%. However, this 6% still corresponds to approximately 4,414 accidents that resulted in 73 fatalities and 6,625 injuries (of which 534 are serious) for the 2,300 miles of UK motorways.

Analysing how these figures are impacted by the CAV technology adoption, we can calculate that the EEBL use case avoids statistically 309 car accidents on average in motorways, corresponding to 5 fatalities and 464 injuries (37 serious). Then if we double the technology penetration level, this number raises to approximately 971 accidents per year with 16 saved lives and 1,457 fewer injuries (117 serious). It is also important to mention that besides the reduction in crash numbers, some crashes that could not be avoided will have rather decreased impact speed, which in return will reduce the number and severity of corresponding injuries.

On the other hand, considerably more accidents occur on urban roads. In the urban "A" roads of the UK traffic network, 21,309 collisions on average are mentioned in the same report, resulting in 57 fatalities and 16,265 injuries (913 serious injuries).

In our simulation, we observed significant safety improvements by 5-11% in varying penetration of three use cases. Extrapolating these improvements to UK-wide urban roads, beginning with the lowest technology penetrations where only a third of the cars in the traffic adopt these CAV technologies, we observe that EEBL and RW bring the highest impact with 852 avoided collisions, resulting in 2 saved lives and 651 fewer injuries (144 serious). Further on, at the 70% penetration, the RW use case avoids 11% of these collisions, corresponding to 1,065 crashes, 6 saved lives and 1,789 fewer injuries (100 serious) [25], [26].

Besides, there is also a financial aspect of the topic. Various methods are used to create statistical valuations of human life, of which one is Value of Statistical Life [27], [28]. It is generally measured by authorities by calculating the gross domestic product (GDP) per head in basic. In line with this, Department for Transport, for example, suggested that the value of a prevented (statistical) fatality for 2016 was £1.83 million [29]. The cost of a serious injury is calculated in a similar aspect, and for 2017, it is £205,000, involving cost elements like lost output, medical and ambulance costs and human costs in previous reports [24], [26].

5.2 Further Cost Extrapolation of ITS Adoption

In the boundaries of this project, we analysed the cost of DSRC technology implementation in specific road patches of motorway and urban environments. However, extrapolating our findings to the full UK scale may demonstrate the future potential costs and help us compare to the expected benefit opportunities.

In cost extrapolation, road types hold an important place, so it is essential to define the right matching between the real traffic and simulation environments. The simulated motorways directly represent the UK motorway network. Hence, the calculated unit costs can be extrapolated to the whole 2,300 miles of UK motorways. UK urban roads, however, have mainly two types: urban "A" roads, and minor roads. The term 'urban' used in this project, mainly represented the urban "A" roads of the UK traffic environment. Hence, the gathered results are extrapolated to 6,867 miles of urban "A" roads across the UK. The following table (Table 5) presents the extrapolated costs of adopting CAV technologies (specifically DSRC) across the UK:

Table 5 Cost extrapolation for motorway and urban environment

	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

5.3 Cost-Effectiveness Analysis

Previous sections presented the extrapolated benefits and costs in detail and Table 6 shows the corresponding monetised comparison.

Table 6 Monetised comparison of costs and benefits of CAV adoption across UK road network

	Motorway (2,300 miles)	Urban "A" roads (6,867 miles)
TOTAL CAPEX	£235m	£248m
CAPEX (per year)	£65m	£407m
OPEX (per year)	£17-54m	£27-65m

If the case of this study would be evaluated only with this pure financial table, we would end up deciding the ITS is not a promising investment. However, the ITS implementation is beyond a simple financial profit motivation. On the contrary, it aims to transform the lifestyle of the public. Hence, it is

essential to remind that cost-effectiveness analysis goes beyond the monetary analysis, when there is either the lack of a monetary equivalent for measured performance indicators or further benefits that are non-quantifiable but essential like social, environmental and convenience benefits as in our case.

When elaborating on our analysis, the first thing to mention should be the boundaries of this study, coming with its assumptions. As mentioned, the field has many contextual complexities as much as the project itself had some practical challenges. They will also be mentioned in detail when identifying the future research directions, but it is essential here to remind that the ITS needs a holistic look to define all the benefits and costs, which will be completed by these future studies.

Hence, despite these limitations on both benefits and the costs sides, we can still draw some inferences from the findings of this study. First of all, we can say that urban roads will become safer especially together with the increasing technology penetration. In line with this, up to 28 lives will be saved, and 318 serious injuries will be prevented each year, only within the boundaries of this study. Besides, the reduction in the travel time of emergency vehicles will also have some indirect effects on the well-being of people in urgent need. Likewise, GHG emission reduction from just the tested use cases is an indicator of how CAV technologies will impact the sustainable life of the future.

It is also critical to mention the expectations in the costs of ITS. Although our findings show the total costs of implementation of CAV technologies and the operation of the ITS outweigh the gathered benefits, we should highlight that these costs belong to a specific CAV technology -DSRC- in its immature period. Along with the developments in technology, both costs would decrease by far, as it gets cheaper or replaced by less-costly substitutes like improved LTE-V or 5G technologies.

6 Conclusions

Overall, we expected to obtain safety benefits from all use cases; however, we could reach our assumptions only in the urban environment. Specifically, we observed a gradual increase of safety benefits in parallel with the technology penetration level for the EEBL (Emergency Electronic Brake Lights), TCW (Traffic Condition Warning) and RW (Roadwork Warning) use cases by analysing changes in crash avoidance effectiveness and average conflict numbers. In the motorway environment, however, we could record a sufficient number of crash cases only in the EEBL use case simulation, where our analysis showed a significant safety impact especially when the penetration of the CAV technologies increased in the traffic. All these improvements will impact directly in our daily lives, by reflecting itself as significant reduction amounts in crashes, decreases the severity of crashes, saved lives and fewer injuries.

Regarding the mobility and environmental benefits, we could not reach our assumptions except for some cases. Mobility improvements were seen only in EVW use case with the decrease of travel time of emergency vehicles. Similarly, we could record some environmental benefits only in the EEBL and RW use cases, as the decrease in CO emissions together with the technology penetration.

However, these findings do not mean that CAV technologies do not have any impact on mobility and environmental benefit dimensions. As mentioned before, ITS implementation includes many contextual and practical challenges and complexities, and our results are bounded by our corresponding assumptions. However, the field can be enlightened further by digging into these future research recommendations that pertain to our limitations.

First, we should remind that as we used a simulation with specific boundaries, we could not observe the impacts in the motorway environment as we intended. So, we encourage researchers to conduct motorway-specialised studies to reveal that potential.

The main focus of this study was the rear crashes because of the practical challenges coming with the immaturity of the field. However, together with the developments in the methodologies and data collection means, the relatively more dangerous front or side crashes can be investigated to increase the safety level of traffic. Because of the same incapability, we limited our analysis to only car occupants in terms of the involving party of an accident. However, it disregards nearly half of the accident casualties in the UK, such as pedestrians, pedal cyclists, and motorcyclists. To have more realistic insights, we still need more studies that can illuminate that area and can give more information about the further impacts of CAV technologies. The same concern is also valid for the consideration of the vehicle types as our simulation included only cars, to sustain our internal validity. However, the inclusion of differences like speed and access limits of different vehicles, or their fuel consumption and GHG emission variations can end up with more real-like conclusions.

Beyond extending our unit of analysis consideration, future studies can also prefer using different measurement perspectives. As much as they can measure the impacts of CAV technologies cooperatively and analyse their synergetic and antagonistic impacts, they can also focus on the impacts of measured dimensions on each other. While some technologies may tap into a dimension, they can harm the other.

Lastly, in parallel with the development of CAV technologies, the upcoming studies can diversify the tested use cases. They would change in time in accordance with the technological capabilities and also with the evolving societal requirements of drivers and other traffic stakeholders. As technology will

become more affordable for large-scale implementation, the extensive application will also extend the expected benefits.

Completion of these different aspects will bring the trade-offs framework that we require to base our strategies on.

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