A macroscopic forecasting framework for estimating socio-economic and environmental performance of Intelligent Transport highways

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Abstract— The anticipated introduction of new forms of Intelligent Transport Systems represents a significant opportunity for increased cooperative mobility and socio-technical changes within the transport system. Although such technologies are currently technically feasible, various socio- economic and environmental barriers impede their arrival. This paper uses a recently developed ITS performance assessment framework, known as EnvFUSION (Environmental Fusion) to perform dynamic forecasting of the performance for three key ITS technologies: Active Traffic Management, Intelligent Speed Adaptation and an Automated Highway System using a mathematical theory of evidence. A c-LCA (consequential lifecycle assessment) is undertaken which forms part of a data fusion process using data from various sources. The models forecast improvements for the three ITS technologies in-line with social acceptability, economic profitability and major carbon reduction scenarios up to 2050 on one of the UK's most congested highways. Analytical Hierarchy Process and Dempster-Shafer theory are used to weight criteria which form part of an Intelligent Transport Sustainability Index. Overall performance is then synthesized. Results indicate that there will be a substantial increase in socio-economic and emissions benefits, provided that the policies are in place and targets are reached which would otherwise delay their realisation.

Index Terms—Intelligent Transport Systems, Environmental Factors, Social Factors, Economics, probabilistic model, Forecasting

I. Introduction

Intelligent transport or ITS can be referred to as a system of systems working in synergy to improve performance. However, not much is understood about the environmental consequences of the rapidly accumulating technology on the roadside. Although solutions such as car-sharing may provide a marginal solution to excess demand in the short term [1], more radical improvements in technology are likely to be needed to move towards sustainability (i.e. environmental, social and economic factors). According to Ferreira and D'Orey [2] the transport sector in the EU-27 accounts for around 25% of CO_2 emissions with 70.9% being attributed to road transport. Managing emissions reduction in ITS is inherently complex due to the presence of an Information Communication Technology (ICT) layer. Whilst this ICT layer facilitates in improved monitoring and communication over congested stretches of road, the carbon overhead of the roadside has also increased through the use of Active Traffic Management (ATM) infrastructure. These technologies have become a cost effective solution compared to alternatives such as road widening in the context of continued increases in traffic density. As technology evolves into a more ubiquitous configuration it is a reasonable assumption that the installation of technology on the roadside due to ATM will recede. Assessing environmental and socio-economic performance of ITS by focusing on the ICT element and technologies themselves has been sparsely represented.

It is predicted that ICT integration will become increasingly ubiquitous, embedded at the user oriented level through in-vehicle and automated driver systems [2-5]. This transformation poses many challenges and naturally features high degrees of uncertainty the further we forecast into the future. While some technologies are identified as having 'evolutionary' or marginal effects such as ATM [6], other systems such as Automated Highway Systems (AHS) are more ambitious [7]. This research aims to provide a forecasting method to effectively account for these factors, providing a decision support tool so that decision makers can prioritise areas of improvement and evaluation of ITS schemes using an integrated consequential modelling approach.

This paper forecasts emissions reductions and socio-economic performance for three key technologies of various scales for a stretch of UK highway up to 2050. Urban implementation is out of scope for the paper. Interviews, the opinions of various experts and dynamically weighted targets provide input to a decision support model. The originality of the EnvFUSION method stems from a priority index which is used to ascertain overall sustainability gains and losses and is a key component currently missing from ITS appraisal due to the limited scope of current assessment practice [8]. Current ITS frameworks only assess service performance based upon a single location rather than the whole infrastructure. In addition, different actors possess different and sometimes conflicting

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requirements in terms of performance which will affect their perspective of the system.

A mathematical theory of evidence is therefore used to consolidate conflicting opinions of stakeholders to determine ITS performance.

The paper has five main sections. Firstly, the authors present a review of frameworks and studies related to the work. The studies aimed to either integrate emissions reduction and socio-technical issues under the heading of 'sustainability' or focus on each individually. Secondly, we provide a methodological framework (EnvFUSION) which describes the main characteristics of the ITS under investigation, the boundary of the study and the performance criteria. Section four describes the model behaviour, data collection and how the criteria is generated within the framework while section five delivers the main results. In section six, details are given of the process to apply a mathematical theory of evidence and generate a priority index. This reflects how environmental and socio economic performance dynamically changes over time with gradual introduction of new technology. Finally, the conclusions close the paper.

II. Related work

A limited number of studies have been carried out which assessed the integrated techno-economic and emissions reduction of future ITS rollout within an inter-urban context [9-10]. Jun and Chunlu [9] proposed a hybrid evaluation methodology for ITS deployment. The benefits were seen to be the explicit inclusion of travel behaviours in evaluation and evaluating the long-term impacts of ITS. Psaraki et al [10] assessed the collective impact of in-vehicle technologies under the banner of driver assistance systems (DAS). These included Adaptive Cruise Control (ACC), Intelligent Speed Adaptation (ISA). AHS and Commercial Vehicle Operations (CVO) were also assessed within the road network of the EU-27 countries. They concluded that AHS was found to be the most promising technology for increasing capacity and reducing CO_2 emissions (by 20%) based on a capacity throughput of 4300 vehicles per hour, while commercial vehicle operations was the most economically affordable.

A comprehensive range of smaller studies have been carried out which aim to explore the individual attributes of inter-urban ITS. Once again the most consistent findings of past research is that AHS offer the most promising benefits in terms of capacity improvement and safety which use algorithms and microscopic simulations to examine capacity when vehicles are organised into platoons [11-15]. Jaworski et al [11] developed a microscopic traffic simulation tool which allowed for the assessment of different traffic control algorithms. The nanoscopic components allowed more detailed observations and the measurement of parameters, such as fuel consumption, that are not easily obtained in most of existing microscopic simulators. Hall and Chin [15] focused on grouping vehicles by destination in order to increase the travel distance between different platoons and the resulting capacity.

In terms of safety and acceptance, Fernandes and Nunez [13] proposed new information management techniques to help improve the stability of the platoon as well as quicker responses to emergencies such as collisions and loss of control. Algorithms using anticipatory information from both the platoon leader and the followers significantly impacts platoon string stability. The simulation results suggested that the effects of communication delays may be almost completely cancelled out. Lai et al [16] estimated that up to 25% of non fatal accidents would be reduced as well as 30% of fatal injuries. Suzuki and Matsunaga [17] revealed that macroscopic shockwave propagation occurs even at a microscopic car-following level and that the speed of shock propagation can be used as an index to evaluate the safety of car-following. Bertolazzi et al [18] as part of the EU project PReVENT developed an integrated system composed mainly of ISA speed restriction and ACC technologies. The system only intervenes when a problem has been detected in the headway or approaching objects based upon speed and distance. The results show that prompt reactions and significant speed correction is carried out before getting into really dangerous situations with user acceptance being high.

Emissions reduction using ITS is covered in [16,19-25]. Bell assessed quantitatively and qualitatively how vehicle technologies and ITS have a role to play in reducing emissions and improving health. The paper specifies a set of measures, i.e., traffic signal control, demand management, road pricing, speed limits, traffic calming and vehicle control systems to achieve this goal. Tsugawa and Kato [23] have presented and discussed various ITS approaches for significant energy savings and emission mitigation demonstrated by field or experimental data. The authors have concluded that vehicular communications play an essential role not only in safety but in energy savings as well. Results from the analysis of ISA by Lai et al [16] estimated 16 million tonnes of CO_2 could be saved in addition to 25.5 billion litres of fuel, although they did not include vehicles weighing over 3.5 tonnes due to their speed being restricted to 100 km/h. For voluntary ISA (the ability to activate speed restriction on command) this related to a saving of 3.4% of CO_2 and 5.8% when mandatory ISA (permanent speed restriction) is active. Khayyam et al [21] developed an adaptive cruise control 'look-ahead' energy management system. The evaluation outcome indicated that the vehicle speed was efficiently controlled through the look-ahead methodology based upon the driving cycle, and that the average fuel consumption was reduced by 3%. In [24] and [25] the authors acknowledged the importance of driver behaviour on fuel consumption and associated pollutants emissions, proposing eco-driving schemes or incentive systems that decreased fuel costs and pollutant emissions.

Other research has explored the cost of implementing ITS [26-27]. Early research such as O'Dea [26] indicated AHS without a significant amount of road tolling would not be preferred over conventional highway operation. Carsten and Tate [27] concluded that implementation of ISA could produce benefit/cost ratios over a 60-year period of either 3.4 (for a market driven future scenario) or 7.4 for a regulatory future scenario, based on the Department for Business Enterprise and Regulatory Reform Central scenario for fuel prices. The costs of deploying ISA tend to be larger in the earlier years and the benefits tend to come later when more vehicles have ISA. However the payback time is not very long, the benefits would outweigh the costs by 2025 under both deployment scenarios.

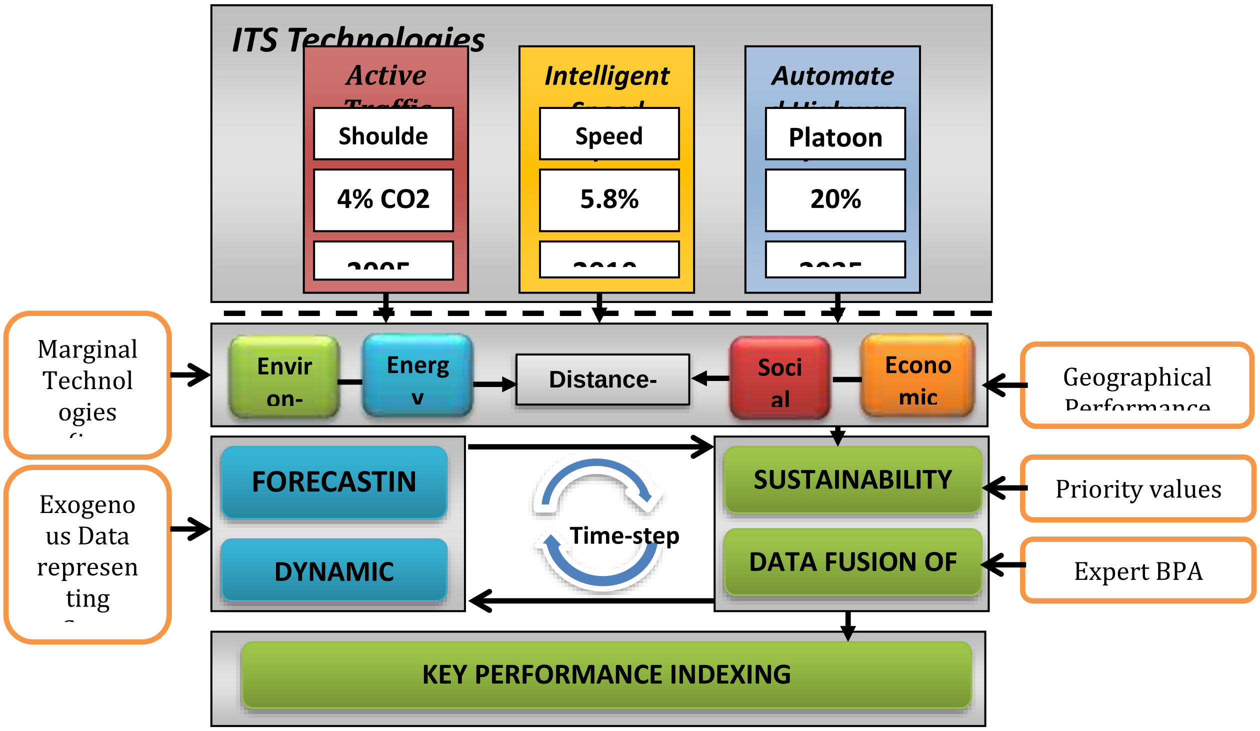


Fig. 1. EnvFUSION forecasting methodology (Source: Author)

III. EnvFUSION Forecasting Methodology

EnvFUSION is an integrated strategic sustainability framework and is the second phase of research conducted in [8]. It consists of three main phases including a Consequential Lifecycle Assessment (cLCA) together with the priority setting and pair wise comparison of the Analytical Hierarchy Process (AHP). The proposed methodology is illustrated in Fig.1. The Ecoinvent database is used to determine emissions factors of materials using a Global Warming Potential (GWP) method [28-29] with a fixed time horizon of 100 years. Dempster-Shafer theory (DST) is used in combination with AHP to form a prioritized Intelligent Transport Sustainability Index from sustainability criteria using subjective quantitative probability assignment. The rationale for integrating AHP and DST is that conventional DST does not differentiate the importance of different types of evidence [30]. In reality, the decisions to proceed with many transport projects are founded on some subjectivities, including the prioritization by decision makers of various targets which aim to reflect socio-economic and environmental objectives. There are therefore advantages in deriving a method that can reflect both objective quantitative and subjective qualitative data. Current ITS systems are assessed using linear fixed data sets but EnvFUSION undertakes the dynamic forecasting of environmental and socio-economic performance using marginal/variable data which allows the consequences of decisions to be evaluated more accurately. Note that the framework is focused at the macroscopic/strategic perspective defined as the level at which technologies cooperate as a system, with input from the microscopic level (such as

evolutionary improvements in material production and resilience etc).

A. Selected ITS Technologies

From Fig. 1. three key ITS technologies were selected for modelling. Each represents a very different configuration and therefore different implementation challenges. The framework has been designed so that it can estimate performance of all technologies whether currently available or anticipated to arrive in the future.

1) Active Traffic Management

ATM represents the current state-of-the-art in dynamic traffic management and is currently being implemented internationally [31-33]. It generally uses a combination of road infrastructure such as gantries, variable message signs, CCTV and signage in order to smooth traffic flow and increase vehicle throughput. This type of ITS was first delivered as a cost-effective alternative to road widening and often extends over a few kilometres of highway or more. ATM has several advantages, it can increase vehicle throughput via displaying digitised messages (including mandatory speed limits) and in most cases when traffic is severe, it allows the hard shoulder to be opened as an additional running lane [33]. ATM can reduce noise and also produce marginal reductions in emissions due to smoother traffic flow.

However, there are some issues with ATM. The technology relies on fixed roadside infrastructure that incurs high levels of embedded emissions during its lifecycle. This is due to the manufacturing processes, also requiring substantial levels of energy during production and its eventual operation.

2) Intelligent Speed Adaptation

Intelligent Speed Adaptation or ISA is a technology designed to restrict the speed limit of a vehicle depending upon the type of road and geographical location [34-35]. It is one of the technologies under the collective banner of DAS. Three types of ISA have been proposed under two main configurations which are Passive or Active. Advisory is passive and informs the driver if the speed limit is exceeded, Voluntary is active and restricts the speed limit at the discretion of the driver, whilst Mandatory makes it compulsory for the system to remain active via judicial law [36].

ISA offers a number of potential benefits including reducing the number of serious and fatal accidents as well as reducing emissions on highways. In more recent studies, the ability of the vehicle to 'know' the speed limit via GPS technologies as opposed to fixed infrastructure will also reduce the need to procure road-side equipment which in turn reduces embedded emissions.

3) Automated Highway System

The automated highway system (or AHS) provides services and support infrastructure required for vehicles to drive autonomously without driver input [12]. This creates improved flow efficiency allowing traffic throughput to increase. At the core of AHS is Cooperative Vehicle Infrastructure Systems in the form of vehicular ad-hoc networks. Vehicular Ad-hoc networks allow the continuous exchange of information such as speed, acceleration, braking and obstacles. During recent trials, integration with cloud computing had enabled vehicles to form platoons, creating digital links which reduce the distance of vehicles at high speed [37-38]. In the future it is expected that AHS could operate independently using Vehicle-to-Vehicle (V2V) communication, although it is anticipated that some form of communication with infrastructure will be still necessary. This will be to monitor connectivity and perform diagnostics, so that some form of centralisation will still be in operation as the infrastructure communicates with a regional traffic control center.

B. System Configuration and Boundary analysis

The geographical area is focused upon the M42 highway at junctions 3a to 7 (Fig.2.). It is one of the most congested transport corridors in England with over 120,000 vehicles passing through daily, acting as a major artery between the north and south of the country as well as serving Birmingham international airport and the logistics of the neighbouring organisations and the National Exhibition Centre. Since 2006, Active Traffic Management has been installed in order to improve rapidly degrading traffic flows. Several benefits have been gained from its usage [39-40]. Capacity has increased by an average of 7-9% with 7% of users encountering no congestion in 2007 compared to 2003. Temporary shoulder running has reduced journey times by up to 24% in northbound and 9% in the southbound direction and has increased the average speed by 5 mph (8 kph). Speed compliance has been improved by 94% at 70 mph (113 kph). Safety has improved with the number of personal injury accidents per month reduced from 5.08 to 1.83. Emissions have been reduced while fuel consumption has decreased by 4%. As ITS technologies are rolled out over time, it is predicted that the M42 corridor may be further improved. However, these improvements are uncertain. The paper attempts to predict the impacts of potential improvements using a recently developed forecasting framework. The time horizon is between 2005 to 2050. 2005 was selected in order to illustrate eight years of historical operation. This allows the models to use existing data which can be projected using exogenous scenarios alongside the anticipated implementation of the technologies selected for study.

Fig. 2. M42 junction 3a-7 traffic corridor near Birmingham city centre. Note the close proximity of Birmingham international airport, neighbouring organizations and the National Exhibition Centre. Active Traffic Management (in red) has been in operation since 2006 resulting in a 4% reduction in CO_2 emissions.

The intial step in the framework was the selection of criteria for assessing the future sustainability of ITS. In practice this resulted from a process of literature study, brainstorming and peer review. Experts within the academic community and road network operators then rated and prioritised the criteria based upon which performance group they viewed as the most important using an Analytical Hierarchy Process [41-42]. AHP enables the user to establish weights for selected impact criteria through the use of pair-wise comparisons and is based upon three elements: the construction of a hierarchy, priority setting and logical consistency [43-45]. According to [46] and [45] criteria within Multi-Criteria Analysis (MCA) can be generated spontaneously.

There are a total of four forecasting models, each belonging to a certain performance group representing a sub-area of 'sustainability'. A number of criteria are generated from a specific model.

TABLE I
PERFORMANCE CRITERIA

Performance Group	Forecasting Models	Performance Criteria
Environment	Road-side Infrastructure	Road-side Infrastructure Emissions
	Vehicle Socio-Environment	Road User Emissions
	ICT Operations	kg CO_2 equivalency. covered by IT Certificates
	ICT Operations	kg CO_2 equivalency per IT task or resource
Energy	ICT Operations	Energy used per task or resource
	ICT Operations	Annual DCIE/PUE for data center
	Road-side Infrastructure	Road-side Energy Consumption
Socio-Economic	Vehicle Socio-Environment	Scheme Compliance
	Vehicle Socio-Environment	Safety
	Cost	Scheme Cost

The performance criteria are illustrated in Table 1**.** The values of the criteria are compared with a Distance-to-target (DTT) method which allows for pre-defined future targets to be compared with the marginal values of the criteria during each timestep within the simulation [47]. These targets can be determined by local, regional and international government bodies and institutions. Whilst DTT was originally an LCA method to evaluate and prioritize the different environmental impact categories, in this paper it has been expanded to incorporate a range of sustainability aspects and modified to give an aggregated score, whilst AHP handles prioritization between environment, social and economic aspects or even specific criteria. The reduction targets can be achieved by improvements in technology. Using a modified version of the Distance-to-target method used by Lin [48], the weighting and percentile of the initial performance state is calculated via:

$$DTT_{(initial)} = ASB_{(initial)} - FST_{(initial)} \qquad (1)$$

or if the target should be of a higher value, (1) is inverted. With $DTT_{(tbase)}$ being the distance-to-target value dependent on the context of the criteria in focus, $ASB_{(tbase)}$ the apparent level of sustainability burden and $FST_{(tbase)}$ the future sustainability target. We refer to sustainability in this context as a subjective value which takes into account all facets of evidence in the form of a sustainability index (representing the group of criteria). The following equations are used to calculate the performance of criterion with negative (2) or positive (3) distance to target values.

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{ASB_{(tyear)}} X\ 100 \qquad (2)$$

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{FST_{(tyear)}} X\ 100 \qquad (3)$$

C. Key Performance Indexing

The data (basic probability assignments and mass functions) are collected for the criteria (table 1) from various sources including experts, IT environmental reports, a cLCA model and direct measurements. It should be noted that sources that use their own grading system will be able to subjectively rate performance using this method. Table 2 illustrates a performance ranking in order to assign belief vectors to the Basic Probability Assignment (BPA) values depending on the result.

TABLE II
INDEX NORMALISED PERFORMANCE RANKING

Grade	BPA Ranking	DTT Ranking	DTT Value
No Target (NT)	0	N/A	0.1 (if value = 0)
Very Low (VL)	0.3	100%-81%	0.2
Low (L)	0.5	80%-61%	0.3
Medium (M)	0.7	60%-41%	0.6
High (H)	0.9	40%-21%	0.9
Very High (VH)	1.0	20%-0%	1.0

Peer experts provided the BPA's either directly or via a pair-wise questionnaire. These different sources were then aggregated using DST.

IV. MODEL BEHAVIOUR AND DATA COLLECTION

As illustrated in Table 1, four models are used to forecast the future state of the highway under investigation. Data was collected for the performance criteria consisting of the infrastructure, vehicles, ICT data center and cost. A number of time-series analysis (including several regression models) were developed in order to generate the predicted future trends in the technologies up to 2050.

A. Road-side Infrastructure Model

Projected cradle to grave embedded emissions were produced based upon expected technology improvements over time. In order to make the cLCA dataset manageable, only the 7 dominant materials in Inter-Urban ITS systems were used. These include aluminium, copper, electrical equipment, plastics, reinforced concrete, steel and toughened glass. All materials used within the model possess their own stock and flow model. Both Primary (Virgin) and Secondary (Recycling) processes are modelled and their cumulative share in the production process is determined by the average European share (UK where available). This data was compiled from various sources including the Ecoinvent database [28] industry reports and academic literature. For example, for 2011 in Europe, aluminium possesses a mean recycling rate of approx 54%, meaning 54% of the demand is processed from end-of-life aluminium scrap (5% energy usage) as opposed to energy intensive mining and processing of bauxite ore with further gains in landfill reduction and export of raw aluminium [49]. Where available, a primary (virgin) and secondary (recycling) emissions factor for each process was applied to the materials using the global warming potential

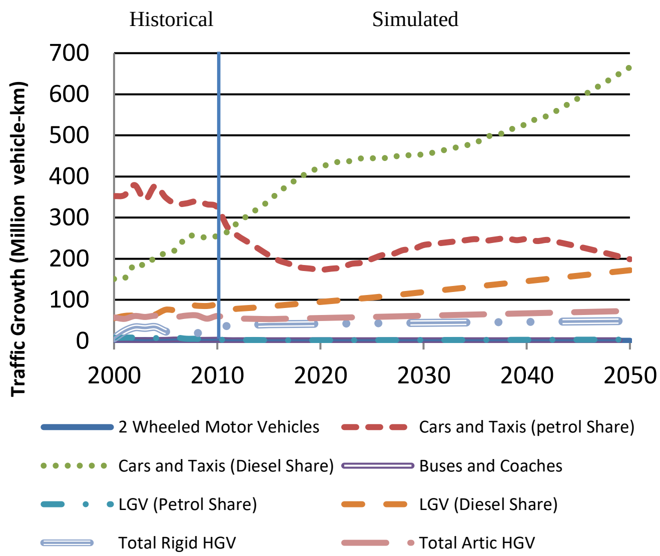


Fig. 3. Traffic Growth of M42 junction 3a-7.

methodology as stipulated by the Intergovernmental Panel on Climate Change's CO_2 conversion factors [50]. Each emissions factor takes into account the full cradle-to-grave process of all greenhouse gas substances including energy and the equipment used to convert raw materials into a finished product. The advantage of using a Consequential lifecycle approach as opposed to Attributional is that the recovery ratios were marginal, therefore a series of confidence intervals were applied to determine the spread of uncertainty based upon the change in contribution of primary and secondary production processes. Although the main disadvantage when using cLCA is the lack of a standard methodological approach to uncertainty, the flexibility of the method allowed for a sophisticated analysis of emissions.

B. Vehicle Socio-Environment Model

In order to accurately predict vehicle emissions over an extended time period (up to 2050), a macroscopic vehicle emission model was created using a series of speed emission curves that were developed in 2009. The advantages of using a macroscopic emissions model is that input data was minimal which would allow a more accurate prediction over a longer time period. Microscopic traffic models that require copious amounts of input data to analyse detailed traffic behaviour such as severe congestion and grid lock scenarios were unsuitable when projecting over a long time period due to prediction accuracy being reduced through complex algorithms having to be simplified at some point to fit the data set [51]. This meant that we could not analyse more detailed driving patterns such as severe congestion. Together with forecasts of national traffic levels and vehicle speeds these are used to predict future quantities of fuel use and road traffic emissions up to 2050 [52-53].

Data for traffic volume was taken from the UK Department for Transport's Average Annual Daily Traffic Flow or AADF (based on the average vehicles per day) for the length of highway. AADF's were created from a number of manual traffic count points. The raw data were then combined from a network of automatic traffic counters (ATC) to calculate a series of AADF's (Annual Average Daily Flows) for each count point (4). To calculate traffic volume, AADF's were combined with the link length and multiplied by the number of days in the year.

$$Traffic_{CP} = AADF_{CP} \times Length_{link} \times 365 \tag{4}$$

Traffic growth is projected via the percentage of expected new vehicle registrations within the west midlands region. Figure 3 illustrates the traffic growth up to 2050 which is currently in-line with national highway traffic growth.

Emission curves were taken from the Transport Research Laboratory and are available in [54]. Raw test data were grouped into a number of vehicle categories, plotting them against the average speed of the test cycle and fitted to a common polynomial expression of the form:

$$EF\left[\frac{g}{km}\right] = \frac{k}{x}a + \sum_{i=1}^{6} \beta_i x^i \tag{5}$$

where a is a constant and β_i, represents the i'th coefficient of x, the speed in kph for a particular Euro standard. The factors are given for a range of different vehicle classes, sizes and fuel types and for each legislative Euro standard from pre-Euro up to Euro 6/VI. For simplification purposes, all factors given are normalised to 50,000km accumulated mileage, although in some cases, scaling factors for emission degradation and fuel quality effects were applied on selected vehicle types (refer to Boulter [52,54])

A further weighting is required to derive a single expression for all vehicles in years according to the mix of vehicle size of a given type in the fleet. Emission Factors were recorded based upon regulated pollutants including CO (Carbon Monoxide), NOx (Nitrogen Oxide), HC (Hydro-carbons), PM (Particulate Matter) and uCO_2 (Ultimate Carbon dioxide emissions based upon direct fuel consumption). For EnvFUSION, all emissions were characterised into CO_2 equivalency using the Global Warming Potential methodology as described earlier in the paper. Note that other vehicle technologies such as hybrid, bio-diesel and electric are not included in the results due to very limited market data. However, by 2040 it is assumed that these vehicles will begin to play a more dominant role as the Euro 6 standard will decline in market share when applied to conventional technologies.

The acceptance of future schemes in the context of this study are based upon the road users compliance with the rules and regulations that are invoked by the ITS service. Inter-urban schemes such as ATM determine their acceptance rate as a percentile depending on whether vehicles do not exceed the variable speed limit that is in place during times of peak traffic congestion. Assessing the future acceptance of different ITS technologies therefore presents some challenges. For example, fully autonomous vehicle technology takes much control away from the road user, including speed, direction and acceleration, therefore scheme compliance is dependent on a number of factors based upon what the service is attempting to achieve. Safety is measured primarily on the killed and seriously injured ratio for a specific section of highway where the ITS scheme is currently operating.

TABLE III
UNIT COSTS OF ITS EQUIPMENT AND MAINTENANCE

ITS Technology & Components	**New Vehicle**	**Retrofit**	**New Vehicle Lower Bound**	**New Vehicle Upper Bound**	**Retrofit Lower Bound**	**Retrofit Upper Bound**	**Maintenance**
ISA Technology Procurement (€/vehicle) including technology depreciation/inflation (2010-2050). [36]							
Advisory	105-70	289-445	88-53	123-88	264-427	306-462	0
Voluntary/Mandatory	234-158	418-532	216-140	252-158	400-515	435-550	10
TOTAL	339-228	710-980	304-193	375-246	664-942	741-1012	10
AHS Technology Procurement (€/vehicle). [10]							
Communication equipment	190	0	130	260	0	0	5
GIS software	120	0	100	140	0	0	0
Sensors for lateral control	350	0	290	410	0	0	10
Sensors for longitudinal control	190	0	140	240	0	0	5
Advanced steering control	200	0	180	220	0	0	5
TOTAL	1050	0	840	1270	0	0	25

C. ICT Operations

In order to estimate the emissions of ICT technology within current and future ITS systems, the data center was analysed based upon a number of criteria. To calculate the operational emissions of the ICT data links, various energy efficiency metrics and indicators were adopted from the literature. The four main criteria for assessing the performance of ICT operational emissions are kg of CO_2 equivalency covered by renewable energy certificates, kg of CO_2 equivalency per IT task or resource focuses on the GHG emissions at the software level (or hardware if data not available), Energy used per task or resource indicates the shared resources towards managing the ITS technology on the highway and is measured in kW/h and finally, the annual Power Usage Effectiveness or Data center infrastructure efficiency [55].

Regardless of technology and the year that is concerned, some form of centralised data center will exist along with road-side infrastructure. For example, Vehicle-to-Vehicle is a form of communication within the Vehicular Network field. The vehicle sends data to other vehicles which can be used to manage safety and inform other road users of oncoming traffic as well as the current capacity of the traffic network [56-59]. However, the communication is handled between road-side infrastructure as well as the vehicles on-board systems which in turn are powered by their battery. For the purposes of this study, in-vehicle systems will become standardized by around 2030 making the ATM road-side technology obsolete and it will be removed from the network.

D. Cost Model

Scheme cost is based upon the economic procurement of infrastructure and systems to operate the ITS scheme. To determine the cost of ATM, the total capital costs per KM of highway were used. For ISA and AHS this includes the cost to procure in-vehicle equipment. For ISA, technology depreciation is illustrated to show the reduction of costs over time as the technology becomes standardised although this is not available for AHS due to the forecast only being available over 15 years which we consider too short to determine in terms of market impact. Table 3 illustrates the breakdown of costs used to procure the equipment and operational running of the three technologies as disseminated by the literature [10,36].

V. MAIN RESULTS

The results and analysis presented here are based upon the methodology outlined in Section 3 and model behaviour in Section 4. The results consist of the impact assessment allocated to the environmental, energy and socio-economic performance groups.

A. Study Analysis

In order to deliver the impact assessment of the three technologies, various assumptions were made. Firstly, it was estimated by the Highways Agency that the ATM infrastructure would possess a lifespan of approximately 25 years, meaning that all systems related to ATM will cease by 2030 as well as the removal of its road-side infrastructure. However, additional infrastructure will be built in order to accommodate V2I communication and the ICT data connections from the local traffic control centre will remain. ISA is simulated based upon the type of system architecture and three different modes of operation (Advisory, Voluntary and Mandatory). According to [27] initial proposals of ISA were to develop roadside DSRC (Dedicated Short Range Communication) beacons to assist vehicles in identifying areas where the correct speed limit is applied. However, the literature dictates that a more autonomous system where vehicles use satellite positioning to identify location with on board digital mapping software was preferred. This means that

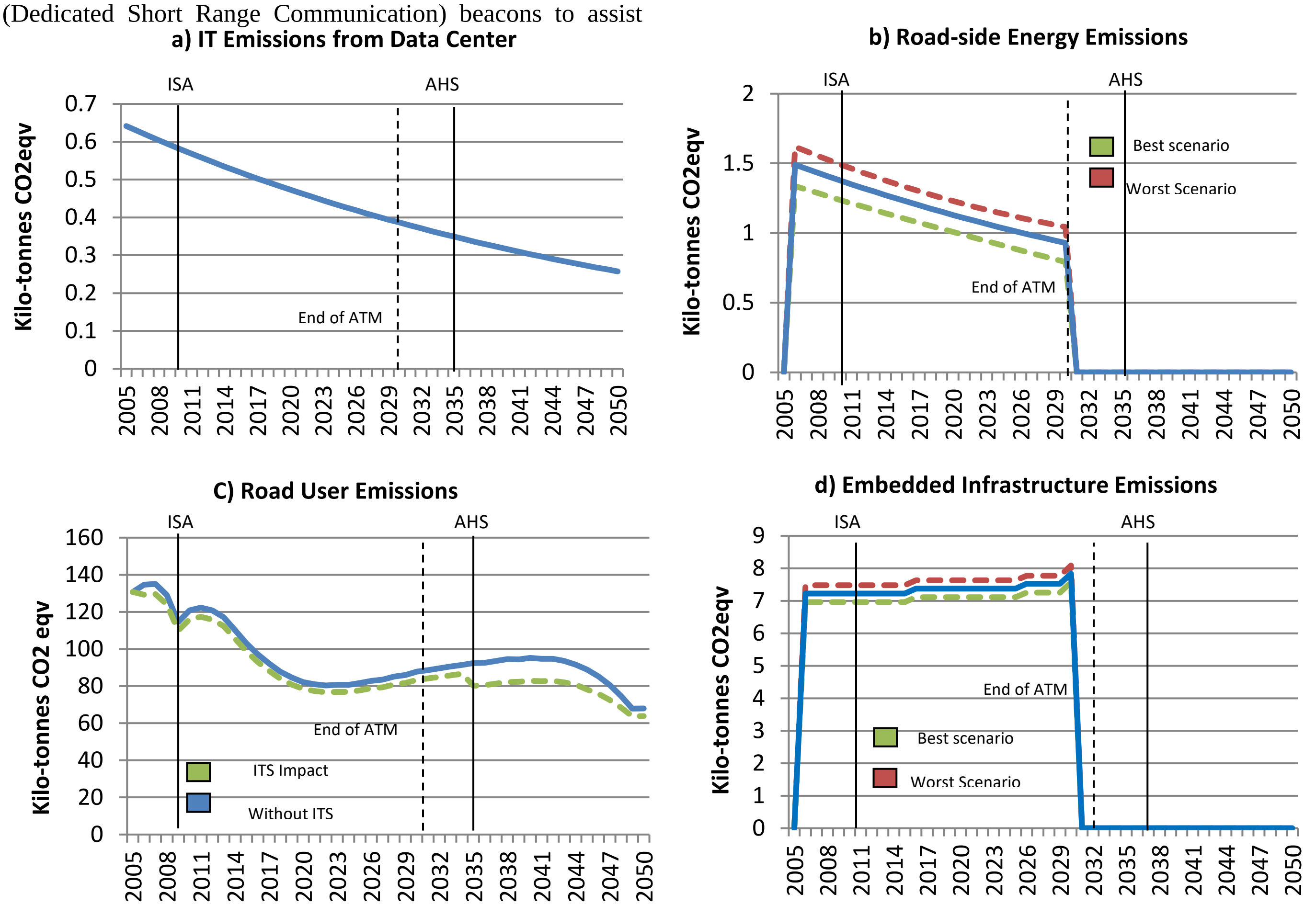


Fig.4. Environmental performance results featuring the four criteria: a) IT Emissions from Data Center, b) Road-side Energy Emissions, c) Road User Emissions, d) Embedded Infrastructure Emissions. The expected introduction of the ITS technologies are displayed as well as the expected end date of Active Traffic Management. Upper and lower data boundaries are displayed in red (worse) and green (best).

additional ITS roadside infrastructure can be negated (the approach adopted in this study). The market forecasts were based upon an authority driven scenario in [60] where full market penetration of 'Advisory' Intelligent Speed Adaptation is expected to be delivered in 2020 with gradual penetration of 'Voluntary' thereafter. By 2045, this scenario forecasts that the 'Mandatory' function will be required by law. These three modes have influenced not only emissions but also safety and cost elements of the model under investigation.

AHS, although in theory possessing rich environmental and socio-economic benefits are more difficult to quantify in terms of market penetration due to uncertainty in technological and policy issues, although numerous studies have been performed [10]. AHS was simulated with the assumption of one car only lane being allocated to platooning in 2035. This is due in part to high performance degradation when mixing different types of vehicles [61]. Infrastructure is built to accommodate V2I communication. As there is a great deal of uncertainty linked to the embedded emissions due in part to a lack of working infrastructure, we believe the emissions to be minimal compared to ATM due to no longer requiring visual display equipment, we therefore did not take such emissions into account. According to [62] in the UK, highways are designed to carry between 1100 vehicles (rural) and 1900 vehicles (urban) per hour per lane (veh/h/l) for both directions, although [10] indicates that this figure may actually vary from 1800-2400 veh/h/l depending upon the behaviour of the driver. It is expected that platooning will allow maximum throughput capacity of the highway to increase to a mean of 4300 vehicles per lane per hour.

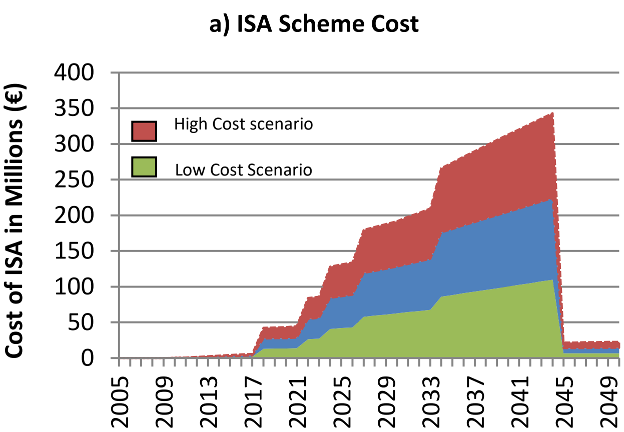
B. Environmental Results

As new technology standards evolve, the emissions of vehicles reduce over time and is based upon the department for transports National Transport Model. There is a sharp decline in road user emissions at 2008 within the historical data set. This is assumed to be a combination of the introduction of the Euro 5 emissions standard being introduced alongside the initial onset of the economic recession as the number of freight vehicles witnessed a sharp decline. The green line in Figure 6 indicates the impact of the ITS systems on emissions while the blue line represents the emissions trend without the assistance of technology.

ATM (4% GWP reduction according to Sultan [20]) saves a total of 99 kilo-tonnes of CO_2 equivalency over its lifespan. ISA is expected to have an impact of 90 kilo-tonnes of CO_2 equivalency saved, although this figure is lower than ATM due to market share not having a significant impact until 2022. As predicted, there is a significant level of emissions reduction when AHS is active with a total saving of 280 kilo-tonnes of CO_2 equivalency.

more expensive depending upon the market share and/or supply of the electronic components required to produce the on-board equipment. There was insufficient data available on AHS systems to apply these assumptions, due to
a lack of technological maturity in the final product.

For ISA according to the 'authority scenario' proposed by Lai et al [36] a total of between 1-1.4 billion Euros would be spent on the rollout of initially 'Advisory' technologies hitting a peak of 92% market share in 2021 with over 220 million Euros invested in technology procurement. During this period 'Voluntary' technologies are expected to possess a market share of 8%. By 2045 'Mandatory' technologies would be



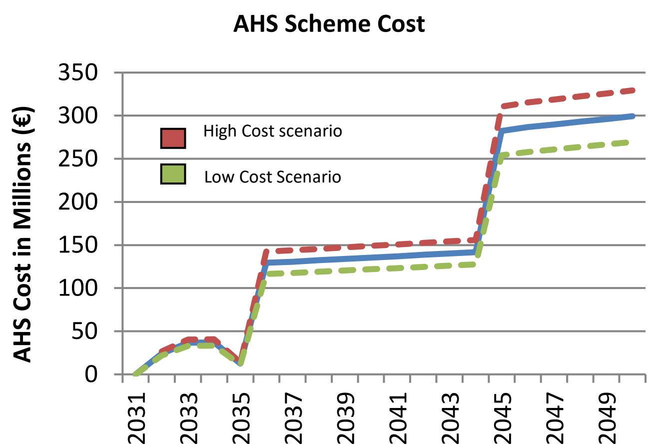


Fig.5. Scheme Cost of ISA (a) and AHS (b) technologies

enforced by government legislation. The investment for AHS would be 2.6-3 billion Euros overall from a start date of 2035. For the purposes of this study, it was assumed that an initial trial run of AHS technology would take place on the M42 stretch of highway, with the technology in some manufactured vehicles from 2032. This assumption is displayed visually in Fig.5b.

The overall safety for the M42 is expected to improve substantially (Table 4). The number of slight accidents is expected to halve due to better compliance with the speed limit and the rollout of advisory ISA technologies. Serious incidents will reduce substantially following increased automation of vehicles and enhanced warning systems. The fatality rate is expected to remain as a zero value although this does not remove the chance of a potentially very serious incident should one of the technologies (i.e. platooning) fail as the systems are not expected to be infallible.

IT emissions (Fig. 4a.) and road-side energy consumption (Fig. 4b.) were simulated based upon the gradual de-carbonisation of the energy grid. For this study it was not possible to obtain sufficient data to determine the KG of GWP per IT task or resource for a sufficient forecast. This would require new metrics and measuring systems for assessing energy consumption at the software level which at this moment in time is unavailable.

Roadside infrastructure emissions (Fig.4d.) shows the residual embedded emissions from the manufacturing and installation process of ATM. In addition, the maintenance of the electronic equipment is undertaken in 2015 and 2025 where the expected failure of electronic units are replaced like for like. It was assumed that after 2030 the emissions are zero due to the removal of the ATM infrastructure and will remain so due to the full deployment of DAS and in-vehicle communication offering the same level of reduction as ATM.

C. Socio-Economic Results

The results concerning socio-economic performance included criteria based upon forecasted scheme compliance, safety and the cost of the ITS technologies.

In order to estimate the cost of the future technologies, statistics on the number of licensed vehicles within the West Midlands region were collected as well as the rate of new vehicles per annum. The expected traffic growth was multiplied against the procurement and operational costs as illustrated in Table 4. The results can be seen in Fig. 7. Upper and lower data boundaries were applied to ISA in Fig.5a. to determine the spread of possible costs with the assumption that the voluntary/mandatory technologies would gradually become

TABLE IV
PROJECTED SAFETY RECORD (PER PERSON)

Year	Slight	Serious	Fatal	Total	KSI Ratio
2012	15	1	0	16	0.0625
2020	7	1	0	8	0.125
2030	2	0	0	2	0
2050	1	0	0	0	0

VI. PERFORMANCE INDEXING

Performance indexing is used here to normalise the results of the models to produce a performance value over time. Although the targets are constants, values of the apparent sustainable burden/benefit will evolve over time and therefore performance will improve or decline at 5 year intervals, based upon the results in Section 5. Decision making in practice (whether in the Transport sector or other sectors) relies on data that can be subject to considerable uncertainties. An indexing method is therefore proposed here that incorporates and combines the subjective opinions of transport experts, governmental stakeholders and academics using DST. DST is based on a mathematical theory of evidence and uses Basic Probability Assignments to determine overall system performance, prioritizing areas needing attention and thus supporting the initial decision making process.

Sustainability Criteria	**Apparent Sustainability Burden/benefit**	**2020 Target**	**2030 Target**	**2050 Target**	**Preliminary DTT Value (2012-2050)**	**% of target remaining (DTT Weight) -2012-2050**
Roadside infrastructure emissions (tCO2eqv)	8,716-0	4000	4,000	0	-4,716 to -0	2012: 54% (0.6) 2050: 0% (1.0)
Road User Emissions (KtCO2eqv)	116-64	80	60	35	-36 to -29	2012: 31% (0.9) 2050: 45% (0.6)
GWP Data Center offset (tCO2eqv)	8-25	20	30	40	12 to 15	2012: 60% (0.6) 2050: 0% (1.0)
GWP per IT resource (kgCO2eqv)	125-25	80	60	40	-45 to -28	2012: 56% (0.6) 2050: 0% (1.0)
Energy used per Resource (mW/h)	27-10	15	10	10	-12 to -17	2012: 44% (0.6) 2050: 0% (1.0)
Annual DCIE/PUE for data center	2.5	1.5	1	1	-2	2012: 80% (0.3) 2050: 0% (1.0)
Roadside Energy Consumption (MW/h)	2,587	1,500	1,000	0	-1,087 to -1587	2012: 42% (0.2) 2050: 0% (1.0)
Scheme Compliance (%)	94-100	94	94	100	6-0	2012: 6% (1.0) 2050: 0% (1.0)
Safety (Killed & Seriously Injured Ratio)	0.0625-0	0	0	0	-0.0625to -0.125	2012: 0.0625% (1.0) 2050: 0% (1.0)
Scheme Cost (Millions/€)	0.89-279	0.70	100	3	-0.19 to -5	2012: 21% (0.9) 2050: 65% (0.3)

TABLE V
DISTANCE TO TARGET PERFORMANCE WEIGHTING FOR M42 JUNCTION 3A-7

A. Estimating performance from future targets

A set of interim targets based upon regional and national forecasting scenarios were added to cover key milestones which are 2020, 2030 and 2050 time points. Table 5 illustrates the distance to target method which was used in order to develop a set of weights based on how far each criterion is from its desired target. The DTT weights originate from the percentage of target remaining from 2012-2050 as described in Table 2 based upon three interim targets This is calculated via first subtracting the target value from the apparent sustainability burden as time moves forward. It has also been assumed that functions delivered by the traffic management services of ATM will be delivered by in-vehicle systems and a reduced level of road-side infrastructure in 2030, therefore a DTT value of 1.0 (i.e. the maximum possible value) has been assumed and applied due to the embedded emissions of the future infrastructure being minimal compared to ATM based infrastructure.

B. Data combination using DST

Alongside the DTT targets, the framework also supports an estimation of performance based on a combination of qualitative and quantitative data from various sources, including experts, models, reports and ICT metrics. Dempster-Shafer theory can handle inconsistencies between data arising from different sources, a common issue with transport and other kinds of data. Applying D-S theory here, $\Theta = \{H_1, H_2, \dots, H_N\}$ is defined as a collectively exhaustive and mutually exclusive set of hypotheses or propositions. A basic probability assignment is then given by a function m: $2^{\Theta} \rightarrow [0,1]$, known as a mass function, which is conditioned by:

$$\sum_{A \subseteq \Theta} m(A) = 1 \qquad (6)$$

$\emptyset$ is classified as the empty set, A is any subset of Θ, and 2^{Θ} is the power set of Θ which consists of all the subsets of Θ, i.e.

$$2^{\Theta} = \{\Phi, \{H_1\}, \dots ,\cdot, \{H_N\}, \{H_1, H_2\}, \{H_1, H_N\}, \dots , \Theta\} \qquad (7)$$

m(A) will measure the belief exactly assigned to A and represents how strongly the evidence supports A. All assigned probabilities are summed to unity and there is no belief in the empty set (Φ). The degree of ignorance is where the assigned probability is m(Θ). As previously described, the goal is to determine the level of belief within the body of evidence (ITS performance criteria) using a plausible set of hypotheses. This can be described by each subset $A \subseteq \Theta$ so that m(A) > 0 where all elements of m together form the body of evidence. m(A) will measure the belief exactly assigned to A and represents how strongly the evidence supports A. All assigned probabilities are summed to unity and there is no belief in the empty set (Φ). The degree of ignorance is where the assigned probability is m(Θ). As previously described above, the goal is to determine the level of belief within the body of evidence (ITS performance criteria) using a plausible set of hypotheses.This can be described by each subset $A \subseteq \Theta$ so that m(A) > 0 where all elements of m together form the body of evidence. Evidence from different sources is combined using Dempsters' rule of combination [63]. It assumes that each information source is fully independent of each other source and uses an orthogonal (independent) sum to combine the multiple belief structures.

$$m = m_1 \oplus m_2 \oplus m_3 \oplus \ldots \oplus m_k \quad (8)$$

$\oplus$ represents the operator of combination. For two belief structures m_1 and m_2, formula 17 illustrates Dempsters rule of combination.

TABLE VI
CALCULATION OF INTELLIGENT TRANSPORT SUSTAINABILITY INDEX

Performance Criteria *BPA's given up to 2030 only	**Intelligent Transport Sustainability Index (2012-2050)**					
	GPR	**BPA's 2012**	**BPA's 2050**	**DTT weighting**	**AHP**	**ITSI Value**
Roadside infrastructure emissions (C_1)*	0.5 X 0.7 X 0.9 X	L = 0.025 M = 0.947 H = 0.031	L = 0.034 M = 0.931 H = 0.034	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.042 2030 = 0.042
Road User Emissions (C_2)	0.5 X 0.7 X 0.9 X 1.0 X	L= 0.016 M= 0.368 H= 0.614 VH=0	L=0 M=0 H=0.029 VH=0.970	X 0.9 (2012) X 0.9 (2050)	X 0.100	2012 = 0.073 2050 = 0.089
GWP Data Center offset (C_3)	0.5 X 0.7 X 0.9 X 1.0 X	L=0.627 M= 0.348 H=0.023 VH=0	L= 0 M=0 H=0 VH=0.994	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.034 2050 = 0.100
GWP per IT resource (C_4)	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L = 0.023 M = 0.974 H = 0.001	L =0 M = 0.015 H = 0.954 VH = 0.030	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.041 2050 = 0.090
Energy used per resource (C_5)	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L= 0 M= 0.652 H = 0.347	L = 0 M= 0.563 H = 0.406 VH= 0.030	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.046 2050 = 0.079
Annual DCIE/PUE for data center (C_6)	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L = 0.969 M = 0.028 H = 0.001	L =0 M = 0.352 H = 0.588 VH = 0.0588	X 0.3 (2012) X 1.0 (2050)	X 0.100	2012 = 0.015 2050 = 0.083
Roadside Energy Consumption (C_7)*	0.5 X 0.7 X 0.9 X	L = 0.529 M = 0.470 H = 0	M = 0.173 H = 0.815 VH = 0.010	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.047 2030 = 0.020
Scheme Compliance (C_8)	0.7 X 0.9 X 1.0 X	M = 0.454 H = 0.545 VH = 0	M = 0 H = 0 VH = 1	X 0.9 (2012) X 1.0 (2050)	X 0.100	2012 = 0.072 2050 = 0.100
Safety (C_9)	0.9 X 1.0 X	H= 0.003 VH =0.996	H = 0.020 VH =0.980	X 1.0 (2012) X 1.0 (2050)	X 0.100	2012 = 0.099 2050 = 0.098
Scheme Cost (C_{10})	0.7 X 0.9 X 1.0 X	M= 0.004 H=0.993 VH=0.002	VL = 0.060 L=0.900 M=0.040	X 0.9 (2012) X 0.3 (2050)	X 0.100	2012 = 0.080 2050 = 0.014

$$[m_1 \oplus m_2](C) = \begin{cases} 0, C = \phi \\ \dfrac{\sum_{A \cap B = C} m_1(A) m_2(B)}{1 - \sum_{A \cap B = \phi} m_1(A) m_2(B)'} & C \neq \phi \end{cases} \quad (9)$$

Where A and B are subsets of Θ and $[m_1 \oplus m_2](C)$ is a basic probability assignment (BPA). The denominator, $1 - \sum_{A \cap B = \phi} m_1(A) m_2(B)$ denoted by K is known as the normalisation factor. $\sum_{A \cap B = \phi} m_1(A) m_2(B)$ is called the degree of conflict between the body of evidence and the process of dividing by k is called normalisation. The larger k is in value, the more sources that are conflicting and therefore the logic in their combination is lower. If k = 0, complete compatibility between the body of evidence is attained. If 0 < k < 1, partial compatibility is achieved. The sources are completely contradictory if k = 1, therefore, the orthogonal sum does not exist.

C. Prioritising Key Performance Areas

Table 6 illustrates the weights for the data fusion, the DTT function and the analytical hierarchy process based upon the index-normalised performance rankings in table 2.

AHP is designed to prioritise criteria based upon a social, environmental or economic focus. The weights originate from interviews with the road network operator. who gave an equal distribution to the criteria therefore all criteria possess equal priority. In this study, note that BPA's are only given up to 2030 on select criteria. This is due to the assumption that the ATM scheme is withdrawn from service and the fact it is difficult to acquire data for the particular criteria for the future technologies. In this instance, it is assumed that the BPA's for 2050 are set at 'very high' (1.0) to reflect the positive changeover in technology from fixed infrastructure to a dynamic ad-hoc network (vehicular network).

Based upon the Intelligent Transport Sustainability Index (ITSI) performance results in Table 6, it is possible to produce a 'unified' analysis to reflect which areas of the ITS scheme are performing acceptably and which areas can potentially be improved. Table 7 below illustrates the priority distribution. In 2020, from strongest (10) to weakest (1), the highest performing criterion (based upon the ITSI performance value) is 'Safety'. This is due to both the future target being met and also the subjective performance grade being rated as 'very high'. It is conjectured that this reflects an increased compliance with the speed limit (also highly rated). The lowest performing criterion is 'roadside energy consumption'. This is due to increasingly stringent targets being set for energy conservation. The assumption is made (for the purposes of the case study) that the procurement of new energy efficient systems is too costly for the road network operator, hence there is no reduction in energy usage. In this scenario there are no carbon reduction strategies in place, despite ICT having a major influence on the emissions and energy of the Active Traffic Management scheme. For 2030 this is reflected by falling levels of performance due to the increasing targets and reflecting no change concerning the use of carbon reduction strategies, although the actual energy consumption is reduced due to gradual de-carbonisation of the UK's energy grid.

TABLE VII
PRIORITY DISTRUBUTION OF PERFORMANCE

Performance Criteria	Normalized Performance Levels and Priority Distributions				
	Apparent Performance Grade (2012-2050)	**ITSI Performance Value**	**Priority (2020)**	**Priority (2030)**	**Priority (2050)**
Roadside infrastructure emissions (C_1)	Medium-V.High	2012=0.042 2050=0.100	6	6	N/A
Road User Emissions (C_2)	High-Medium	2012=0.073 2050=0.041	8	5	4
GWP Data Center offset (C_3)	Low-V.High	2012 =0.034 2050 =0.100	7	8	7=
GWP per IT resource (C_4)	Medium-High	2012 =0.041 2050 =0.090	3	1	5
Energy used per resource (C_5)	Medium-Medium	2012 =0.046 2050 =0.079	4	2	2
Annual DCIE/PUE for data center (C_6)	Low-High	2012 =0.015 2050 =0.083	2	4	3
Roadside Energy Consumption (C_7)	Low-V.High	2012 =0.047 2050 =0.100	1	3	N/A
Scheme Compliance (C_8)	High-V.High	2012 =0.072 2050 =0.100	9	9=	7=
Safety (C_9)	V. High-V.High	2012 =0.099 2050 =0.100	10	7	6
Scheme Cost (C_{10})	High-Low	2012 =0.080 2050 =0.014	5	9=	1
OVERALL PERFORMANCE	Medium-High	2012=0.555 2050=0.795			

With the correct knowledge and training, the energy efficiency of the data center may be improved, for example by following the guidelines in the EU Code of Conduct for Data Center Energy Efficiency. By 2050 however, the architecture of the system is expected to change removing the ATM roadside infrastructure although it is assumed that infrastructure relating to the management of AHS as well as a centralized data center will still be in place This would have a direct impact on energy, embedded emissions and the cost of the scheme (the worst performer in 2050).

VII. CONCLUSIONS

The rollout of a number of Intelligent Transport Systems is already underway in many countries, with new and innovative ITS schemes anticipated in both the near term and longer term future. What is required now is an improved understanding of of such ITS technologies. This paper has considered one future scenario in terms of the implementation of new technology, although many scenarios are possible to reflect potential changes at both the macroscopic level (the services the technologies deliver) and the microscopic level (improvements in material production, vehicle technology and electrical devices etc). Widespread deployment of the new ITS applications in practice is, of course, dependent upon a number of factors. The macroeconomic landscape and the global economic downturn affect R&D investments, which may impact on the long-term needs of AHS. Interoperability and standardisation issues need to be resolved to achieve large-scale integration of vehicle and transport infrastructure and provision of services over different platforms and countries. In particular, in-vehicle systems face the hurdle of requiring 100% deployment in motorized vehicles to function. However, this penetration problem is a common issue for a variety of other V2V or V2I applications. Safety-related applications are a particular example that requires high penetration rates for effectiveness and must be promoted to communicate their advantages. Reaching this level of deployment may require legislative action, for example for retro-fitting of existing motorized vehicles with appropriate ITS systems. The EnvFUSION framework has been designed so that it can be applied to urban areas and technologies in addition to highways, provided that the data is available and in order to assist in decision making. The main strength in the framework is, however, the ability to take uncertain or conflicting data and estimate performance over time using dynamic targets. The framework is therefore flexible and can be adapted to the needs of the user and the context, whether at the regional, national or international level. The results in Fig. 4c. show that ATM will offset greenhouse gas emissions by 99 kilo-tonnes of CO_2 equivalency over a 25 year lifespan, whilst AHS is anticipated to save 280 kilo-tonnes of CO_2 equivalency over 15 years of operational usage. However, this offset is largely dependent on assumptions such as the level of market penetration and traffic growth. Nevertheless, the results of the ITSI index indicate a high level of future performance is anticipated concerning emissions reduction and in terms of safety, energy conservation and the monetary perspective.

Future work includes improving the vehicle emission model so that more complex vehicle behaviour can be modelled. We aim to investigate the energy and GHG savings that arise from the implementation of ITS measures for hybrid, electric vehicles and bio-diesel, which currently have limited market penetration. The cLCA can be improved to take into account advances in material production over time, focusing on resilience, advances in production technologies and enhanced recycling processes. Finally, the development of metrics to estimate the level of ICT energy consumption at the software level is a high research priority due to the expected increase in use of ICT in future transport technologies.

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