Appraisal and Evaluation of Interurban ITS: A European Survey

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***Abstract*—Intelligent transport systems (ITS) have at their core technological systems that work together to improve transportation performance. However, this performance becomes uncertain when the technologies themselves are scrutinized alongside the benefit they deliver. This paper reviews the background theory, issues, and gaps concerning the assessment of performance for ITS, as well as a review of frameworks proposed by various authors in the field. This paper provides an original contribution through 1) identifying twelve evaluation framework requirements, 2) proposing corresponding solutions to business, and 3) the introduction of four key performance areas for ITS. The key requirements of ITS from the literature include improved geographical focus, reducing conflicting stakeholder involvement, and consolidating elements of ITS that are currently calculated in isolation. Current indicators are biased toward economic benefit. The definition of four key performance areas are Adaptability, Sustainability, Standardization, and Data Management. To conclude, the introduction of technology requires a paradigm shift, in terms of reorganization and realignment of the scope of conventional transport system evaluation. This is needed, in order to maintain accuracy and more fully capture performance aspects when appraising ITS.**

***Index Terms*—Economic factors, environmental impact assessment, intelligent transport systems (ITS), social factors, sustainability, transport appraisal.**

I. Introduction

TRANSPORTATION performance covers a wide variety of characteristics such as traffic throughput, environmental, social, and economic issues. The introduction of intelligent transport system (ITS) schemes on the highway has increased complexity by also introducing sociotechnical sources of uncertainty as a result of the use of information and communications technology (ICT) and the need to manage and store data assets. We refer to sociotechnical systems as the feedback relationships between the road users and the technology. In this paper, sociotechnical sources include sources of uncertainty arising from the interrelations between road users and the technology. This covers a large number of different and sometimes conflicting data. Uncertainty also exists in estimating the full range of emissions arising from ITS projects, due to the construction of gantries and technological hardware on the roadside. These new factors require a review of the definition of transport systems performance and a reorganization and introduction of the key criteria that are used to assess transport schemes.

This paper discusses the evaluation issues in ITS projects, in order to determine the problem rationale. The framework requirements are then outlined, which drive the possible solutions. This paper then defines four key performance cornerstones, which aim to provide a skeletal framework for the development of performance criteria. The outcome of this review is intended to stimulate the debate around development of a unified official framework, which can be used to better track the performance of ITS schemes regardless of configuration. A secondary outcome will be the ability to identify potential improvements in the technologies themselves, where performance suggests that improvement is needed, and suggest potential solutions to business.

II. Evaluation Issues in ITS Projects

This section explores the literature on the current evaluation processes (ex-ante and ex-post) and performance monitoring of ITS projects.

A. Factors in Implementation

Limited historical data exists in order to assess whether certain ITS projects are successful [1]. Certain ITS impacts (according to Newman-Askins *et al.* [2]) are of a qualitative nature (such as driver comfort) and problematic to quantify. In addition, limited work has been carried out to explore the relational attributes of ITS projects and their associated impacts, making it difficult to transfer the results in space or time. ITS evaluation should ideally be undertaken to the same degree of rigor as that for conventional transport projects. The most common type of evaluation in ITS projects are currently nonrandomized controlled study designs, with the most popular being the controlled before and after study. These studies are used largely by road network operators for conventional network solutions, such as building another road, in order to illustrate perceived benefits of the ITS intervention [3]. An appropriate framework must be created, in order to integrate ITS evaluation methods into the existing transport planning methodology [4]. The implementation process for an ITS system is affected dynamically by different actors [5]. Three actor groups (users, manufacturers, and authority) determine the dynamics of implementation. The road user plays a role in initiating consumer demand through to accepting the service, depending on the role the service is intended to provide. We refer to

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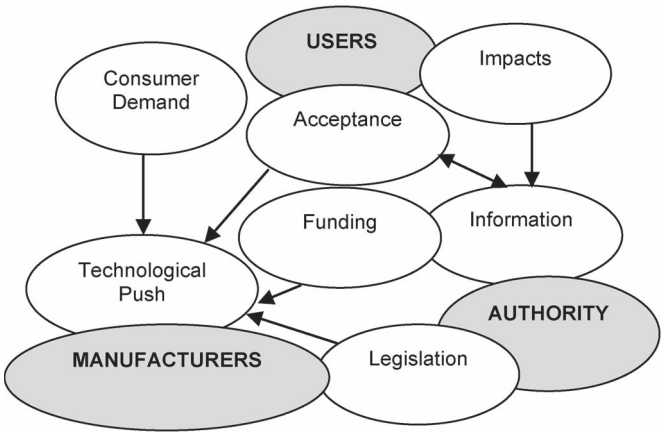

Fig. 1. Actors affecting implementation (source: Bekiaris *et al.* [5]).

authorities such as the standard bodies and legal enforcement agencies such as the police and government.

The second group of actors includes vehicle and system manufacturers. They possess the highest level of knowledge on technological competence of the proposed systems. However, product research and development is partially dictated by the end users' needs and whether they are willing to pay for the new service. Manufacturers are dependent upon legislation and are bound by specific rules and regulations. The third group of actors includes the authorities (such as the standard bodies and legal enforcement agencies such as the police and government), legislation, and administrative practices. Their goal is to protect the welfare of users and higher level objectives. They therefore review new system implementations and the overall impact that the new technologies will have upon society (users and nonusers) as well as make sure that their policy operates within legal boundaries. User opinions may direct the implementation of the service. Fig. 1 illustrates the actors affecting the final implementation process.

Grant-Muller and Usher [6] developed a propensity model to determine whether ITS services provided environmental and economic benefits. First, underlying drivers and a synthesis of empirical evidence was applied to determine whether such systems can be developed. Second, modeling was used to determine whether policy priorities among national and international stakeholders reflect a propensity for ITS deployment in order to yield those benefits. The results indicated that ITS, in general, can variably reduce the carbon intensity of negotiating distance (refer to article for detailed results). However, the evidence base concerning the real-life environmental and climate change related impacts of ITS systems is not yet at the required level of detail or routinely and rigorously collected to fully support investment and related policy decisions. Future challenges included an acknowledgement of the enduring strategic priority of both economic and environmental sustainability, particularly in the post economic recession. Coherent cross-sectoral policies are needed at the national (and where appropriate, international) level, which allow full evaluation of ICT-related measures that impact beyond the transport sector. The research also concluded that a governance structure is needed that is sufficiently flexible to support financial investment and maintenance that may vary in scale between different types and configurations of ITS. The findings reveal a need for a better understanding of ITS benefits. Communicating cross-sectoral synergies, in terms of benefits and solutions, is also a necessary element to this.

B. Quantifying ITS Benefits

Social, economic, and environmental impacts are unpredictable; therefore, their risks and costs are difficult to envisage. Some authors [7]–[10] have attempted to measure the influence of ITS through simulation (including virtual reality/virtual environment tools). However, other authors [11], [12] have attempted to utilize existing transport appraisal tools, such as cost-benefit analysis (CBA), to determine the impacts of ITS. The disadvantage of applying CBA to the environmental elements specific to ITS is that the discount rate that is applied to tangible assets also applies to the impact of emissions. Environmental impacts should be assessed separately, regardless of timeframe [13]. Others have measured ITS performance using three different approaches, including delay cost, fuel cost, and emission modules. The influences, according to Thill *et al.* [14], were measured before and after the system. From an ICT perspective, ICT project selection is based upon an evaluation of qualitative and quantitative objective measures such as business goals, benefits, project risks, and resource allocation [15]. These measures illustrate a direct parallel, when attempting to select viable ITS projects. The research in ICT project evaluation is significant, but made more difficult due to socioenvironmental priorities.

C. Proposed ITS Evaluation Methodologies

The current literature proposes various solutions for measuring ITS impacts and suggests that the evaluation process for ITS projects should differ from the methods used for traditional road projects. Newman-Askins *et al.* [2] argued that the cause-and-effect relationships between service components are more complex than measuring components in isolation. The most important criteria for an effective ITS methodology are described as follows:

1) The evaluation should be transparent and allow for simple updating of impact parameters.
2) The methodology should provide an accurate output and should be objective, i.e., without bias.
3) The methodology should allow a comparison between the evaluation results for ITS schemes and those for conventional transport projects.
4) Evaluation should include rigorous sensitivity testing and not apply false precision to the estimated impacts.
5) It should consider the combined effect of implementing various combinations of ITS.
6) The methodology should avoid the double counting of benefits.
7) The base and project cases studied should be based on the same operational conditions.
8) The evaluation should account for feedback effects (e.g., latent demand from increased highway capacity).
9) The approach should be a dynamic one and comprehensive of a collection of ITS technologies working in concert (a system).

Several of these criteria also apply to the evaluation of conventional projects. An ITS evaluation methodology must be capable of evaluating the impacts of individual components of the project as well as the impacts of various combinations of components. For this reason, an ITS evaluation methodology must be more sensitive and detailed than existing evaluation models, due to the relational dynamics of the ICT equipment, the road user, and the vehicles. It is important to note that the ITS service implementation is not just represented in a singular location but that it may span multiple geographical areas. For example, an asynchronous transfer mode infrastructure is controlled from a traffic control center (TCC), which may be based at some distance from the highway itself. It can then be argued that an environmental and socioeconomic analysis should take into account the energy requirements of the datacenter residing in the TCC, as well as the effects of the ITS scheme on vehicle emissions. This is a fundamental aspect of ITS appraisal, i.e., that the assessment of ITS should be performed at the system level, regardless of geographical location.

When selecting an appropriate evaluation method for ITS projects, it is important that a balance exists between complexity and cost of evaluation, as well as the cost of the project itself. One of the main barriers to performing a successful ITS evaluation is the lack of historical data. Very few exist due to the evolving nature of ITS projects and differences between technologies [2]. Their work suggested that ITS projects are merely enhancements to increase efficiency to the network and it may not be necessary to anticipate a full economic analysis. When forecasting future technologies, the economic analysis should be performed at the system level, taking into account additional vehicle costs, ICT and roadside infrastructure, and the energy consumption of the service. It is therefore preferable to analyze the environmental and socioeconomic benefits using conventional appraisal methods, such as CBA, cost-effectiveness analysis, multicriteria analysis, and lifecycle assessment, although environmental aspects should be accounted separately from other benefits. This is a critical factor in the creation of an ITS performance framework. As an example, He *et al.* [1] proposed an ITS evaluation framework for measuring the advantages of an urban ITS management and command system in the city of Beijing. First, the most important indexes are chosen to compare traffic systems performance ex-ante and ex-post for the ITS project to be implemented. According [1], indexes can be obtained from official sources early, and they can also illustrate the advantages of ITS implementation. In their research on the enhancement of traffic capacity, the economy of human resources and the reduction of traffic accidents are indexes of ITS performance. Since the units of these indexes are very different in terms of values, they cannot be easily implemented as a whole. Therefore, they recommend that the indexes should be turned into economic advantages. For example, the enhancement of traffic capacity will arguably allow the saving of cost in road construction, traffic congestion, and pollution control. This is currently a major issue not only in ITS but also in transport economic evaluation, as multiple data types must be converted to an economic value in order for the evaluation to be relevant. Any proposed framework has to be developed in a way that could combine data with different values, and this is one of the main priorities in developing ITS performance metrics.

The application of ITS will arguably save the cost of law enforcement and emergency services. Traffic accidents are expect to decrease due to the use of an intelligent traffic management system. Finally, the reduction of traffic collisions is likely to mitigate direct economic loss and reduce the fatality rate. ITS social and economic benefits can be calculated through the accumulation of economic benefits within the indexes. A closer analysis of the framework may take into account the levels of pollution. However, it is still quite ambiguous. It ignores the direct energy usage of the infrastructure and instead focuses primarily on economic benefits; neither does it take into account the energy requirements of the datacenter that communicates with the electronic equipment. A common argument with existing ITS performance frameworks is that they only cater for specific technologies in unique circumstances. They do not support continuous evaluation and service improvement of an ITS service's compatibility toward a low-carbon environment and, as a result, give no indication of the expected environmental benefits. As part of the FP7 EU project CONDUITS, Kaparias *et al.* [16] and Eden *et al.* [17] proposed a framework for urban traffic management and ITS. Key performance indicators were developed, focusing on traffic efficiency, safety, pollution reduction, and social inclusion. The final stages of the project saw the validation of the framework through an application to four case studies. The framework also supports forecasting through the implementation of various policies and technologies, enabling transport authorities to evaluate them before making a decision. However, the same weaknesses arise, such as a high level of ambiguity in the total emissions of the ITS scheme, a lack of analysis of energy emissions, and finally no assessment of the embedded emissions.

D. Green ICT Policy

ITS performance evaluation should incorporate the emissions and energy consumption of the ICT architecture connected to the schemes. While it is important for the transport system (including roadside infrastructure and eventually vehicles) to be enhanced by measures implemented in order to achieve a low-carbon vision, it is also necessary to measure and maintain a carbon-neutral data management system [18]–[21]. According to Shah *et al.* [22], the future market for green IT services will exceed three billion pounds by the end of 2013. The use of ICT within intelligent transport provides an integral platform to implement and maintain advanced traffic services. ICT infrastructure that is directly involved in maintaining ITS must also be environmentally balanced [23]. For example, variable message signs and other infrastructure used by ATM are controlled via a regional TCC through data linkage. A datacenter is used to store control systems, which in turn requires energy to operate, and must therefore be taken into account to ensure the emission estimate is accurate. An ICT "greening" plan has been developed by the U.K. government, in order to address these issues [24]. According to the Cabinet Office [18], it was proposed that, by 2012, the use of ICT by the Government's Central Office Estate will become carbon neutral. Since the

U.K. has an overall target to reduce greenhouse gases (GHGs) by 26% or more by 2020 and 80% by 2050, it is essential to ensure that all elements that contribute to climate change are accounted for. Other countries also possess similar targets, which need to be achieved. The U.K. Government recently created a Director General level post of Chief Sustainability Officer. Governmental objectives now include performance indicators for achievements against Sustainable Operations on the Government Estate (SOGE) targets. It is hoped that, by 2020, the government will aim to achieve a carbon-neutral ICT lifecycle.

ICT is perceived by Crooks *et al.* [25] as a main source of providing organizational efficiency and can directly enable mass reduction in carbon offsetting by increasing performance in decision-making and resource management. According to Feng *et al.* [26] and Crooks *et al.* [25], energy consumption from datacenters is argued to be at least or greater than the carbon footprint from the aircraft industry (800 t or roughly 2% of global emissions). In relation to ITS, the methods and approaches proposed by the British Computing Society and similar agencies are equally important in determining how energy-efficient current and future transport systems will become. A model is introduced, which analyzes the energy output of a vehicular network using the geographical adaptive fidelity management protocol. The overall goal of their research was to provide a model for a software utility, which would control the energy consumption of vehicular networks. Since the networks are *ad hoc*, certain transceivers (estimated to be between 25 and 40 mAh) that are not connected to the vehicles must be placed within the infrastructure. They require their own power supply to function, which will increase the level of energy required. The Committee for Climate Change [27] predicted that climate levels will have peaked by 2016 but should begin to fall based upon the distribution and implementation of new technologies.

III. Framework Requirements

A. Level of Focus

It is apparent that current ITS appraisal frameworks only assess services based upon a single location rather than the whole system. They do not take into account components that are located off the physical road space. For example, in the U.K. when assessing the contribution of emission savings of ATM, the Highways Agency did not, apparently, take into account the emissions of the datacenter used to control the roadside infrastructure [28]. Assessing performance at the system level (taking into account that all services that are linked to the ITS scheme rather than focusing on a single geographical area) would allow the contribution of emissions and energy consumption to be more accurately reflected in the analysis of system performance.

The review of the literature also indicates a lack of emphasis being placed on performance between the actors of the ITS service. Different actors possess different and sometimes conflicting requirements, in terms of performance, which will affect their perspective of the system. Therefore, an analysis of social, economic, and environmental output between the actors (road network operator, manufacturer, etc.) will improve estimates of performance for future ITS technologies such as intelligent speed adaptation (ISA) and automated highway system (AHS). This is due to each technology being configured in a significantly different fashion, although their overall aims are similar in terms of reducing traffic congestion and improving traffic safety. It is also difficult to assess the performance between schemes, due to differing configurations in technology, scale, and cost. Performance could be assessed, regardless of differences in configurations and scope of the technologies. The ability of transport and ICT services to operate under a low-carbon future requires analysis from these perspectives. As He *et al.* [1] highlighted, a lack of historical data when assessing future performance of ITS requires a reliance on very limited real-world studies. The evaluation process in the performance framework should include rigorous sensitivity testing and not apply false precision to the estimated impacts.

Finally, index values used in current appraisal frameworks are monetary due to the difficulty arising in combining different value types into an absolute whole. One solution is to weight each index value with a priority value so that a combination of different values could be normalized through a holistic performance indicator. An interscheme comparison supermatrix containing ITS performance indexes between schemes could then be generated. When monetizing the environmental cost savings using traditional methods, the results are inaccurate due to use of a single discount rate applied over long time periods, when in reality they can only assess environmental aspects in the current timeframe when using methods such as CBA. A proposed framework would ideally apply dual discounting for future ITS schemes, in order to measure environmental cost savings for periods of more than 20 years, particularly when forecasting into the future. Table I illustrates a summary of the key deficiencies in the ITS frameworks that currently exist, as well as areas that have remained untouched and require further support.

Proposed solutions are also provided in Table I by the authors, which aim to stimulate debate but are recognized as just one approach that could be applied. Fig. 2 illustrates a flowchart of the proposed ITS appraisal solutions applied to the U.K. transport appraisal guidance [29].

B. Environmental Issues

According to the Department of Energy and Climate Change of Her Majesty's Government [30], the transport sector should contribute a saving of 19% on CO_2 emissions, between 2018 and 2020, based on 2008 levels. Sentance [31] proposes that, in the same year, there is also a possibility for carbon reduction through improving the technical efficiency of vehicles (including vehicle throughput and engine performance). King [32] proposes that, by 2030, vehicle power plants will be 50% more efficient in terms of CO_2 emissions (based on 2007 levels) if current trends are followed. According to Sentance [31] and Eddington [33], the majority of the transport infrastructure will be utilized for future ITS iterations and will still be operational by 2050 (albeit through sufficient maintenance and

TABLE I
DEFICIENCIES IN ITS PERFORMANCE EVALUATION FRAMEWORKS

Deficiency	Analysis and Challenges	Proposed Solution	Applicable ITS Technologies
1 Current indicators biased towards economic ITS benefits	Index values such as emissions reduction are monetary due to difficulties arising in combining different value types into an absolute whole.	Each index value is weighted and given a normalised performance value so that combination can be achieved through a holistic performance indicator.	Covers all ITS technologies.
2 Limited geographical focus	Current ITS frameworks only assess the services based upon a singular location rather than the whole system.	Assess performance at the system level taking into account all services that are linked to the ITS scheme such as the data center etc.	Active Traffic Management; Advanced Traveller Information Systems; Automated Highway System.
3 Conflicting stakeholder involvement	Different actors possess different and sometimes conflicting requirements in terms of performance which will affect their perspective of the ITS system.	Allow performance evaluation to be made by consolidating opinions from multiple stakeholders into a method which can handle conflict.	Covers all ITS technologies.
4 Decision making isolated at various levels of implementation	Decision making is currently isolated at regional, national and international levels.	Introduce three separately stacked layers for each level of focus and show the contribution of the ITS schemes performance between each layer.	Covers all ITS technologies.
5 Data collection uncertainty	Lack of historical data when assessing future performance of ITS instead relying on very limited real-world studies.	Evaluation should include rigorous sensitivity testing and not apply false precision to the estimated environmental and socio-economic impacts.	Covers all ITS technologies.
6 Elements of ITS calculated in isolation	No standardised accounting methodology for integrating emissions of the infrastructure, ICT and vehicles into the overall analysis as well as economic benefits gained from the offset of carbon.	Integrate the environmental lifecycle results of the ICT data center, vehicle emissions and embedded emissions of road-side infrastructure to provide a cross-sectional contribution of total emissions generated from the ITS service.	Active Traffic Management; Advanced Traveller Information Systems.
7 Limited assessment of greenhouse gases	Current transport appraisal frameworks only take into account certain gases such as CO_2 and therefore do not represent the complete potential of ITS services effects on climate change.	Convert greenhouse gas emissions into Global warming potentials where available, to maximise the accounting accuracy of the ITS schemes contribution to climate change.	Covers all ITS technologies.
8 No scheme comparisons	Difficult to assess the performance between schemes due to vastly different configurations in technology, scale and cost.	An inter-scheme comparison super-matrix containing normalised ITS performance indexes between schemes for each category.	Covers all ITS technologies.
9 Limited socio-technical analysis	Technical performance areas such as data management and adaptability are not cross referenced with environmental and socio-economic areas.	Define performance areas and performance relational analysis using dynamic modelling methodologies.	Advanced Traveller Information Systems; Automated Highway System.
10 Monetary environmental benefits inaccurate over long-term	Monetising the environmental cost savings inaccurate due to solitary discount rates applied over long time periods.	Apply dual discounting for future ITS schemes in order to measure environmental cost savings for periods of more than 20 years. Monetary environmental benefits should be reflected in lifecycle assessment.	Covers all ITS technologies.
11 Lack of linkage between regional and national emission targets	Lack of reporting on how ITS schemes can assist in meeting national emission targets within the evaluation.	Weight the level of emissions offset against the distance of a specified target being reached.	Covers all ITS technologies.
12 Feedback Uncertainty	Latent demand from increased capacity unclearly represented on certain technologies	Develop a microscopic system dynamics model which can handle the full range of traffic feedback.	Covers all ITS technologies.

restoration). However, considering one of the goals of the research is to reduce the use of traditional infrastructure, the cost of maintaining future infrastructure should be kept to a minimum. This is an indication from the literature that the limitations of space, maintenance costs and environmental issues with traditional infrastructure (tarmac roads) and widening, results in such approaches becoming unfeasible in the future. Therefore, the performance framework should also assess the embedded emissions of alternative and future ITS services. According to Patey *et al.* [34], no studies at that time have focused on the embedded lifecycle emissions in the construction, operation, and disposal of ITS schemes. One exception is the work of Kolosz *et al.* [35], where the emissions from ICT and infrastructure for their whole lifecycle were considered alongside the potential gains through traffic flow efficiency. As the majority of future emission targets are aimed at reducing the level of CO_2 to a certain degree, environmental accounting frameworks do not accurately illustrate the contribution of the ITS scheme to climate change. Converting GHG emissions into global warming potentials (GWP) would increase the accuracy in estimating the ITS schemes' contribution to climate change. ICT works as an enabler within ITS systems, in order to improve the performance of the road network by improved control and supervision. Apart from recent developments by Kolosz *et al.* [35] and [36], there is very little evidence to date of a framework designed to assess the combination of environmental performance with the wider impacts (such as safety and social aspects) of ITS technologies.

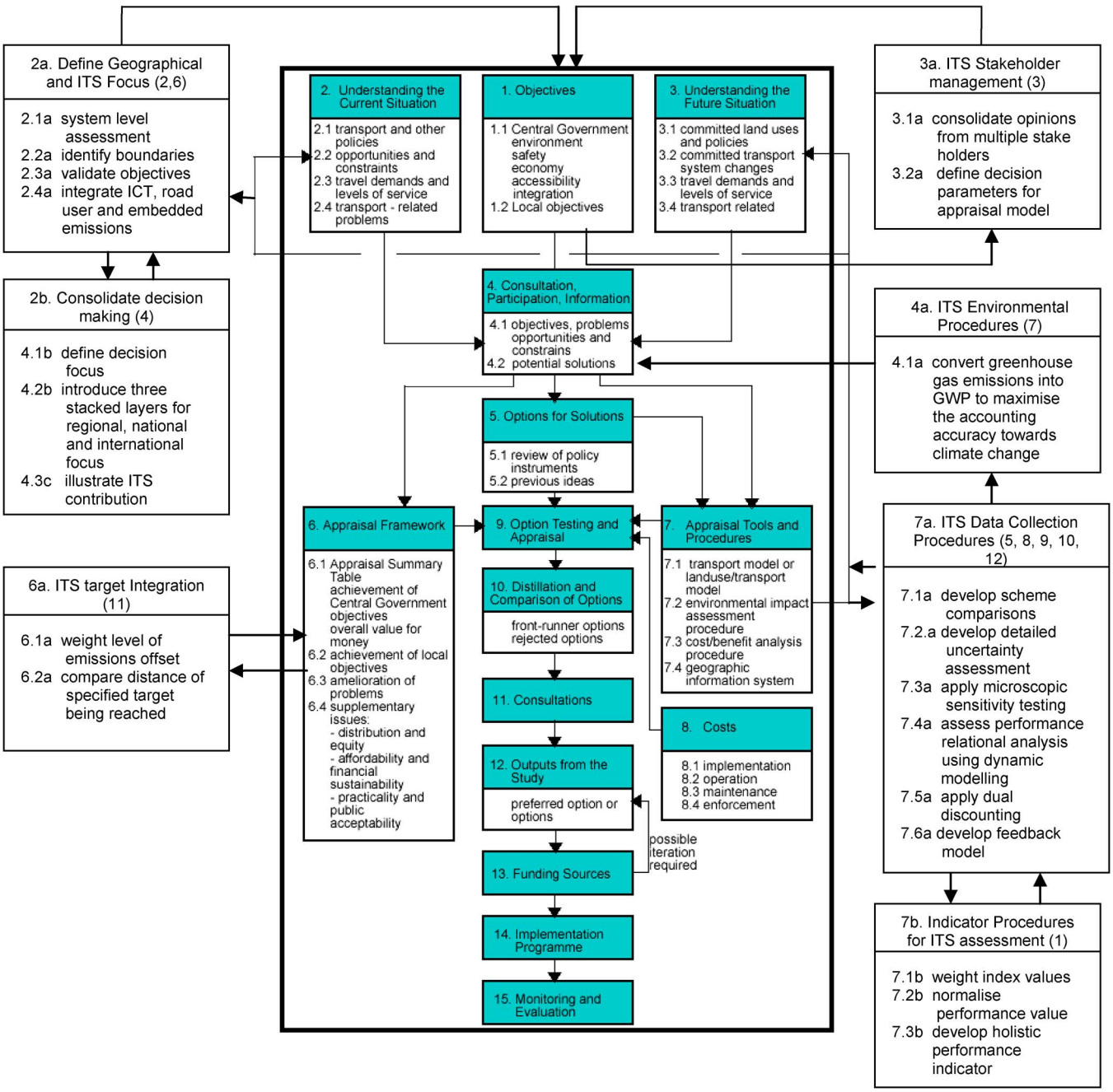

Fig. 2. Flowchart of proposed ITS appraisal solution applied to U.K. transport appraisal guidance.

There is currently no standardized methodology for integrating emissions of the infrastructure, ICT, and vehicles into the overall analysis. Further strategies are needed to integrate the environmental lifecycle results of the ICT datacenter, vehicle emissions, and embedded emissions of roadside infrastructure, to provide a cross-sectional contribution of total emissions generated from the ITS service.

C. Socio-Technical Issues

Some authors maintain that a future transport network [37]–[39] will consist of a variety of integrated wireless communications delivering seamless real-time data to the transport network. Transmitting these data becomes complex due to a wide variety of data types and transmission sources [40]–[42]. In addition, these data sources need to be protected against malicious attacks (viruses, hackers, etc.) by maintaining its integrity [43]. To achieve this, several factors must be taken into account:

1) What are the data types and how can the network deal with them?
2) What are the available transmission sources and are they accurate and efficient?
3) What measures are in place to protect the wireless networks from software interlopers?

Technical performance areas, such as data management and the level of adaptability, are not cross-referenced with environmental and socioeconomic areas; therefore, hidden cause-and-effect relationships may alter the performance during a forecast of future systems. For example, wireless networks that maintain safety-critical functions, such as maintaining vehicle headway, may fail due to interference from the natural landscape. This will have a cascading effect on not only safety but also the acceptance of the technology involved. Defining performance areas and relational analysis using dynamic modeling methodologies would allow an increased understanding of how technical systems affect emission reduction, safety levels, and acceptance in future ITS implementation.

D. Performance Categories

Performance management in ITS must take environmental issues into account, in order to assist in the reduction of climate change. Low-carbon manufacturing processes resulting in the creation of ITS infrastructure should be in place to negate the effects of GHG emissions and energy wastage [44], [45]. The European governments' targets of not only reducing transport but also applying pressure on providing a "green" ICT energy consumption means that maintaining a low-carbon future is a high priority [18], [25], [26], [46]. Additional performance measures are needed to estimate the success of carbon and energy initiatives within ITS (transport and ICT perspectives) in order to achieve the goals for the future. Performance in ITS also requires a certain level of adaptability. Vehicular networks must be able to maintain a constant connection and level of resilience. For example, wireless networks may encounter interference from natural landscapes (hills, mountains, etc.) and artificial data blockades such as tunnels [47]. In addition, a sociotechnical perspective must indicate how future ubiquitous services will behave and perform in a way that allows road users the guarantee of optimal safety, navigation, and origin-destination planning [48], [49]. Indicators must be developed to define how ITS services maintain user adoption. The performance definition should focus on standardization and allow true network compatibility across the varying technologies both now and in the future. Network standards should be developed, which are universally compatible with infrastructure, data types, and transmissions [40], [50], [51]. Four major areas of performance within ITS can be mapped within the context of environmental and socioeconomic performance, with each possessing specific attributes, as follows:

1) Data Management and Information Complexity (IC);
2) Sustainability;
3) Standardization;
4) Adaptability.

The proposed areas represent general performance categories for managing ITS within an interurban environment (although they could be applied to urban-based services.) Each area features its own performance index, and the ITS performance management frameworks' route to optimization (see Fig. 2) is expressed by the "standards highway". All performance areas should be linked via cause and effect variables. They represent the technical side of maintaining *continual service improvement* (ITS is built from an ICT/technical infrastructure; therefore, performance measures must be implemented objectively). They also aim to reinforce the governance of existing and future transport appraisal based upon governmental policy [30]. The framework to be developed should also be compatible with the appropriate government targets. Due to the current issues surrounding climate change, it is necessary that any current or future ITS-based solution must be aligned with the targets of these bodies.

E. Solutions to Business

Accurate performance management in terms of ITS will provide several solutions to business. First, an official standardization framework will enable successful monitoring of a large number of information sources and sift them, presenting the relevant facts to the transport stakeholders and enabling the road network operators to make decisions about taking up opportunities. As a result, businesses will be well informed about ITS developments in the rest of the world, particularly Europe. This will enable road network operators to exploit these opportunities and become more integrated with Europe, thereby improving services to travelers on the network.

Appropriate guidelines for data collection and traffic feedback will reduce the uncertainty in the capabilities of each ITS technology and generate scheme comparisons, allowing business to more accurately predict the expected performance of technologies, potentially reducing project overheads, and providing better decision making on which technologies should be selected. Relational linkages between emission targets will allow stakeholders to apply improved leverage on internal and external emission quotas, reducing overall business losses to emissions penalties.

The weighting of each ITS performance factor will depend heavily upon the level of role and prioritization that the stakeholder has, in terms of their relationship toward the ITS technology. It is advisable to first apply a balanced weighting to determine default performance before prioritizing; however, the weights should be developed based upon a quantitative (where a distance-to-target method could be used) and qualitative approach (for the general opinion of the stakeholder advisory team).

IV. Performance Management for ITS: A Proposed KPI Suite

A. Data Management

This section discusses data management as one of the four foundations for ITS performance evaluation. It is separated into factors concerning IC, managing information through ITS and some of the challenges overall.

Defining IC: Information-based complexity is defined by Traub [52] as the study of:

> "infinite-dimensional continuous problems. These are problems where either the input or the output are elements of infinite-dimensional spaces."

IC is concerned with the ability to handle various amounts of data. Due to the ad hoc nature of vehicular networks, some data may be hard to compute or even track because of the unpredictability of traffic movements [54]–[56]. Meier *et al.* [57] refer to IC within the context of ITS as a selection of data, which are organized within a suitable model. With reference to response times, the terminology reflects an IT-based data retrieval measure. Data management was chosen as a performance category in this paper as ad hoc vehicular networks rely on communication via data packets, which are sent via a vehicle or through a node point within the system (traffic control, Global Positioning System (GPS) transmission, etc.).

Possessing the ability to measure the response time of the network will offer significant insight into the improvement of data retrieval [58]. Estimating IC is a low-resource (data processing) task, which can include several variables over a fixed period (time and space, for example). Estimating the level of information offers significant insight into the improvement of data retrieval [58]. IC within traditional systems uses minimal resources due to the simplistic algorithm that is involved. However, managing the complexity of data within a transport network can become very difficult to maintain. Therefore, performance measures should be developed, in order to not only measure levels of complexity but also to assess and manage data integrity and to reflect how it can be integrated in future highway systems.

Managing Information Through ITS: With respect to intelligent transport networks, the management of data will involve assessing how efficient vehicular networks are at dealing with multilayered driving information that is sent from multiple sources to a receiver based within a vehicle. It is apparent from the research that the majority of the data being transmitted will be based upon localization techniques, in order to track the vehicle as it progresses through the network. GPS receivers are the most common example; however, the literature also discusses sensor networks, cellular localization, and wireless devices that operate upon a particular frequency. Boukerche [55] refers to the limitation of existing GPS technology in that current systems are not always available as well as the accuracy being generally low.

Different ITS systems have been proposed based on functionality; however, they lack the ability to interconnect with other systems, leaving certain data items redundant. McQueen and McQueen [59] refer to a solution known as an ITS architecture. This architecture is a data model, which supports multiple layers of data that can be connected to other networks in order to share and maintain information within repositories. Meier *et al.* [57] proposed an IT Architecture known as iTransIT. The architecture has the ability to utilize real-time data in order to connect to legacy systems that are currently being used by the network. It is noted that they use different quality-of-service rules compared to traditional management systems. They propose a layered data model, which can support data modules from different systems. The data can then be processed using filters to remove "noise" and irregularities in the information. The various forms of communication offer varying levels of complexity. In addition, there is a real-time data stream, which requires an instantaneous update of information.

Zhang *et al.* [60] defined an ITS architecture called D^2ITS, which aimed to support the current state of ITS and to provide a framework for future advanced services. It is supported by large amounts of data that are collected from various resources. They are described as systems that would allow users to interactively utilize data resources that pertain to transportation systems, access and employ data through more convenient and reliable services to improve the performance of transportation systems, and realize and extend the functions of the six fundamental components of ITS. Examples of real-time data streams include lane guidance and critical traffic information (to alert the driver of any upcoming obstacles) to the more advanced technologies such as automatic navigation and control of the car via platooning. At this point, the amount of information that is circulating across the network is very dense; therefore, suitable measures must be developed, in order to manage this complexity and harness the data stream by delivering an efficient service.

Potential Issues: Zargayouna *et al.* [61] proposed a travel middleware framework utilizing a set of agents, which will minimize IC via automated message passing. The system is referred to as a traveler information system, and the overall objective of an agent is to receive the information relating to the appropriate driver information at the right time. The literature in relation to vehicular ad hoc networks (VANETs) [43], [62], [63] discusses several overheads, which may affect the complexity of the information being sent through the network. This includes traffic validation (i.e., the vehicles on the road) and the protection of the network from abuse [64]–[68].

Network abuse in ICT systems includes two groups of attack, which can also be applied to ITS systems: *passive* and *active.* Passive is prone to "eavesdropping" when spying on data, which may act as reference points for vehicle location; *active* may include a direct impact such as denial of service and bogus information attacks, which can scramble and rearrange data. There are a variety of different attacks, which are grouped under these two forms of attack. According to Parno and Perrig [62], a denial of service is where an attacker attempts to jam all communications, therefore blocking all critical data. Message suppression attacks are used to confuse drivers into choosing the wrong lane or forming a traffic jam on a section of the road. A fabrication attack occurs when a false message is sent to the network. The final and most malicious attack available is the alteration attack, whose main purpose is to alter data to suit the goal of the attacker. This type of attack can be very serious, particularly if the data that refer the driver to an oncoming obstacle are deceived because the vehicle may not actually exist. Understanding the structure and flow of data within ITS is a prerequisite to developing the correct standards, in order to control key aspects of a VANET and other forms of communication. How these data are secured is vital to ensure the safety and integrity of the system [69], [70].

B. Standardization

This section discusses the current status of ITS standards within Europe and the rest of the world. These standards are then critically evaluated, and the research approach to the key performance indicator (KPI) of the standards is also discussed.

TABLE II
ITS TRAFFIC AND TECHNICAL STANDARDS

Standard	Body/Established	Description
CEN/TC 278	Technical Committee of the European Committee for Standardization, Established 1991.	"Standardisation in the field of telematics to be applied to road traffic and transport, including those elements that need technical harmonisation for intermodal operation in the case of other means of transport." (CEN/TC 278, 1991)
IEEE SCC32	Institute of Electrical and Electronics Engineers. Established 1991.	"shall be responsible for coordinating, developing, and maintaining standards, recommended practices, and guidelines related to ITS within the scope of IEEE interests." [53]
ISO/TC 204	International Organization for Standardization Technical Committee. Established 1992.	"ISO/TC 204 encompasses standardization of information, communications and control systems in the field of urban and rural surface transportation, including intermodal and multimodal aspects, traveller information, traffic management, generally referred to as Intelligent Transport Systems (ITS)."
TC 22		
ETSI/ TC ITS	European Telecommunications Standards Institute (ETSI) approved the creation of a Technical Committee on ITS. Established 2007.	"Standards, Specifications and other deliverables to support the development and implementation of ITS Service provision across the network, for transport networks, vehicles and transport users, including interface aspects and multiple modes of transport and interoperability between systems, but not including ITS application standards, radio matters, and electromagnetic compatibility (EMC)."
ERM	Electromagnetic Compatibility and Radio spectrum Matters	
IETF MEXT	Internet Engineering Task Force (IETF) featuring MEXT (Mobility EXTensions for IPv6)	to enhance base IPv6 mobility by continuing work on developments that are required for wide-scale deployments and specific deployment scenarios.
ITU-T	International Telecommunication Union (ITU), Telecommunication for Motor Vehicles,	ITU- T's main aims is to research, develop and promote standardisation solutions through ICT systems. They have promoted ITS in the last 30 years.

Standards Highway: Intelligent transport networks have been implemented on the highways for a period of at least 30 years; however, there is still a significant lack of standardization within methods and approaches according to the literature. Vehicles are not well standardized other than in the very basic fact that most (but not all) have four wheels. Standardization should reinforce the compatibility of systems working together, which should provide a basis for future intelligent transport development. For example, within wireless networks, application protocols have been proposed by several authors, such as Torrent-Moreno [71], who propose a new standardization protocol (IEEE 802.11e), which delivers improved reliability or IEEE 802.11p for vehicular network control [72]. However, there are many wireless protocols that exist and have not yet been chosen in order to support a suitable driver data stream.

In addition, a network infrastructure that is free of physical obstruction must be proposed from a top-level perspective, which will have a suitable capability to perform at a strategic (nationwide) level. This is to ensure that communication, product versions, and protocols within the infrastructure are standardized, which will lead to a more efficient level of control and compatibility. Internationally, various standards are being developed, which are focused toward the various actors, technological systems, and services. Standards are being developed for ITS based upon organizational bodies, which have prior knowledge and a record of international standard excellence. It is rare that new organizations emerge with the role of developing standards. Existing bodies have used their wealth of experience to articulate their own definitions and perspectives (usually from an ICT background) to maintain technological service equality.

The services and products that are offered to ITS are placed within a rough field known as telematics, which is arguably a combination of interdisciplinary fields brought together. According to the literature [73]–[75], telematics covers ICT-based communication, including vehicle-to-infrastructure communication, wireless technologies, safety, information access, vehicle tracking, fleet management, online navigation, and road-user charging. The main advantage of incorporating such standards within ITS is not only to ensure compatibility between transport services and ICT but also to increase the competitiveness of the vehicle manufacturers and ICT to deliver a superior product. The various bodies that control the makeup of standards for ITS are split into two distinct groups: standards development organizations (SDOs) and national standard bodies (NSBs).

Current ITS Standards: At the time of writing, the Highways Agency (U.K. based) has a project underway known as *ITS Radar International*. Its main task is to assess and maintain awareness of current standards that have been introduced by the NSBs and SDOs within Europe and internationally. According to their recently updated *ITS standards tracking database*, the Highways Agency have already adopted numerous standards that have been developed internationally [51]. Of the standards listed earlier, the Highways Agency have adopted a select few from each of the technical bodies. Several telematic traffic standards exist, and their activities are defined in Table II.

The International Telecommunication Union (ITU) is recognized as the leading United Nations agency for formulating policy for the latest technological and communication issues and is based in Geneva, Switzerland. Formed 145 years ago, ITU's recent mission is to provide telecommunication solutions through ICT in both slowly developing and mature regions and cultures of the world. Originally, ITU supported ITS by delivering requirements through radio communication. However, since 2003, they have been working on other areas, combining their expertise into the majority of transport services and ICT. In their recent ITU-T Technology Watch Report [50], research reported on the standardization of ITS technology in several key areas includes the following: vehicles, human users, roadside elements

TABLE III
ITS TRAFFIC AND TECHNICAL STANDARDS

Board/Panel	Body/Established	Description
ICTSB - ITSSG	ITS Steering group (ITSSG) via ICT Standards Board (ICTSB)	The ICT Standards Board (ICTSB) established an ITS Steering Group (ITSSG), with the European Commission as observers, co-ordinating among three European Standards Organizations (CEN, CENELEC, ETSI), a number of ICT standards consortia, and representatives from ITS stakeholders from the public and private sectors.
APSC TELEMOV	Advisory Panel for Standards Cooperation on Telecommunications related to Motor Vehicles.	An open forum bringing together the leading international standardization organizations as well as industry consortia, as partners engaged in advancing ITS and vehicular telematic standards.

(infrastructure), and external information through ICT services. They perform a cross-comparison, which highlights how each SDO contributes to standardization. The goals and objectives from all standards have a number of commonalities. They have been created to develop specifications, harmonize technological interoperability, and provide services in the support of ITS and the sustainability of ICT to ensure optimal use of road transport. However, it should be noted that the standards that each SDO/NSB develops will only contribute to the interests of the organizational body in question. In other words, each SDO may only cover certain aspects of standardization related to their own market identity and research interests. For example, the IEEE's SCC32 standard will focus on software development and wireless protocols that will be used in the development of ITS systems; however, it may overlook environmental (climate change, low carbon, etc.), political, and social aspects. Therefore, NSBs were developed, in order to bring a suite of standards from multiple sources together. This is accomplished, in order to give clarity, to standardize goals and objectives, and to reach vital conclusions, which will enable an agreement between the SDOs. The following NSBs have been identified in Table III.

C. Adaptability

This section discusses ITS adaptability, which includes system compatibility, geometric robustness, and response times. The research approach to the KPI is also discussed.

Defining Adaptability: Response times, data stream robustness, and resource sharing within vehicular networks are placed into a KPI known as Adaptability. They are based upon the estimated speed of delivery for real-time data, the ability to utilize different connection modes and compatibility between different infrastructure and networks (including data) and to reinforce geometric connectivity robustness [47]. Zhao and Cao [58] refer to multihop delivery as a very complicated process because of the frequent disconnection of the vehicular network. This is because the network is very free-form, and therefore, data that are sent to a specific vehicle might be delayed. They therefore propose several vehicle-assisted data delivery protocols (VADD) to forward data packets (data stored in electronic clusters) to the best possible route with the least delay. The data in particular will be (in most cases) safety critical and must be predicted using a set of algorithmic expressions. Wu *et al.* [76] proposed a mobility-centric data dissemination algorithm (MDDV) for vehicular networks. Vehicles perform local behavior based upon their own knowledge, while having a global outlook. This approach arguably saves decision-making time; therefore, this specific KPI will be important in the selection of an appropriate algorithm to maintain the flow of information.

Response Times: Parno and Perrig [62] discuss the need to maintain high response times since this will directly affect the safety of the driver. This is because the data stream will be operating in real time; therefore, there must be a quick level of response, which will directly relate to the level of complexity within the data stream. There will need to be an additional investment in resources, in order to cope with the additional infrastructure. The infrastructure may include sensors attached to the vehicle or other solutions such as an information generation and sharing framework [56]. In addition, it will be necessary to design (and eventually implement) a suitable level of middleware, which will be utilized to maintain the highest performance possible. Response times can be measured in a variety of ways. *Throughput* in network performance terms is the number of messages successfully delivered per unit time. Data throughput is controlled by available bandwidth, as well as the available signal-to-noise ratio and hardware limitations. Various metrics are available; however, since vehicular networks are dynamic (*ad hoc*), the performance may vary.

Geometric Connectivity Robustness: Spanos and Murray [47] created a function known as *Geometric Connectivity Robustness*. However, this term has been redefined in this paper to reflect adaptable networking within the KPI, for example, to take into account loss of signal and geometric barriers (such as tunnels, etc.). Any proposed ITS evaluation framework needs to not only measure response times but also reflect the need to remain connected to the network despite various motion and geographical constraints. The function, therefore, has the role of reflecting the motion constraints brought on by the requirements of connectivity.

The framework is designed to coincide with other mobile networking research and models. Most control algorithms do not base their requirements on information flow rather the connectivity. There is never a need to identify shared variables between vehicles. However, the number of connections (according to Spanos and Murray [47]) has a definite bearing on the stability and performance of the network. In addition, work has been produced on embedded cooperative radars, in order to gain a high signal output for guided services in tunnels [77]. While this work was originally designed for trains, it may have practical use in combination with platooning, which is also a guided technology.

Resource Sharing: Resource dissemination and data fusion are of particular importance when communicating with the network [78]. Such communication that occurs in vehicular networks includes peer-to-peer (P2P) networking [79]–[81]. The network must be able to successfully share resources in an efficient manner [82]. This has a direct impact on the speed of resource dissemination, which depends on the complexity of information within the network. According to Galluccio *et al.* [80], the performance parameter (i.e., service capacity) is still an open problem within mobile networking. Their research performed a service capacity analysis on P2P networks, where nodes are dynamically moving and dependent on the current state of the traffic. Various actions of the vehicle are accounted for, including acceleration, breaking, and minimum safe headway between vehicles. In addition, because the network is in a constantly moving state, resource dissemination is performed.

Their proposed model proved to be valuable in estimating the effect node density and traffic correlation has upon information dissemination within the traffic network. Lin *et al.* [83] discuss the evaluation of a new generation of telematics system, which incorporates a social media-based network using novel-based multicriteria decision-making (MCDM) techniques. The criteria are not independent but incorporate feedback mechanisms, and the system features navigation, safety, communication, information, and entertainment as possible criteria along with a set of weights.

D. Sustainability

Due to the current issues surrounding climate change, it is necessary to be aware that any current or future ITS-based solution must coincide with the targets of these bodies, in particular, those of the U.K. and Europe. International bodies have their own specific criteria. The scope of the environmental evaluation for an ITS scheme is proposed to comprise three main foci: the roadside infrastructure, the datacenter situated within the regional TCC, and the vehicles traveling on the highway. Any future framework should also aim to assess the energy consumption of future vehicular networks, although the ability to undertake this will depend on whether historical data are available.

Vehicle Emission Modeling Issues: Modeling of vehicle emissions can be undertaken on several levels. According to Ferreira and d'Orey [84], emission models can broadly be categorized into macroscopic, mesoscopic, and microscopic models. The macroscopic approach, which is based upon average travel speed, has been the most common methodology used for estimating vehicle emissions [85]. In Europe, for example, most inventories of exhaust emissions at the fleet level, or for a city as a whole, are still calculated according to the COPERT methodology (a software program to calculate air pollutant emissions from road transport developed from the European MEET project) [86]. These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions. An important drawback of this methodology is that it calculates emissions per kilometer for vehicle trajectories using primarily the average speed. Although the overall trip speed is an important factor influencing emissions, instantaneous speed fluctuation plays a greater part. For the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each resulting in very different fuel consumption and emission levels [84], [87]. For the compilation of emission inventories of large areas and over long time periods, this microscopic effect may be ignored, and the results from the macroscopic models may give reasonably good estimates. In relation to estimating ITS service performance over a longer time period, this appeared to be the most suitable option as microscopic accuracy becomes less important over a long-term forecast and may give a more accurate estimate. Mesoscopic models that take traffic dynamics partially into account by partitioning the traffic situations in several classes have been less widely used.

More sophisticated hybrid approaches, such as the Assessment and Reliability of Transport Emission Models and Inventory Systems (ARTEMIS), which is a 42-month project started in 2000, are still in their infancy [88]. Mesoscopic models use more disaggregate trip variables, such as the average speed, the number of stops, and time stood in congestion, to estimate a vehicle's emission rates on a link-by-link basis. Some regression models that were developed were found to predict fuel consumption and emission rates of hydrocarbons, carbon monoxide, and nitrous oxide to within 88%–90% of instantaneous microscopic emission estimates [89]. Microscopic emission models overcome some of the limitations of large-scale macroscopic models mainly by considering individual vehicles' dynamics and their interactions. Emissions and fuel consumption are estimated based on instantaneous individual vehicle variables that can frequently be obtained (e.g., second by second) from a microscopic traffic simulator or another alternative source (e.g., the GPS data logger). Commonly, these parameters are divided into the following two categories: vehicle parameters and traffic/road parameters. Vehicle parameters include, among others, vehicle mass, fuel type, engine displacement, and vehicle class. On the other hand, network parameters (traffic and road conditions) account for instantaneous vehicle kinematics (e.g., speed or acceleration), aggregated variables (e.g., the time spent in the acceleration mode), or road characteristics (e.g., road grade). Due to the fact that microscopic emission and fuel consumption models have higher temporal precision and better capture the effects of vehicle dynamics/interactions, they are better suited to evaluate the environmental gains derived from an ITS measure, such as the virtual tape library system. Several microscopic models have been proposed by the scientific community. These models can be classified into emission maps (speed/acceleration lookup tables), purely statistical models, and load-based models [90]. Major contributions in this field were given by Akcelik and Besley [91], Barth *et al.* [92] with the comprehensive modal emission model, Ahn *et al.* [93], and Cappiello *et al.* [90] with the emissions from traffic (EMIT) model. In addition, the recent work of Barth *et al.* on dynamic ecodriving provides interesting results with up to 12% emission improvement for the algorithm that was developed [94]. Several models that focus on the macroscopic and mesoscopic level seemed

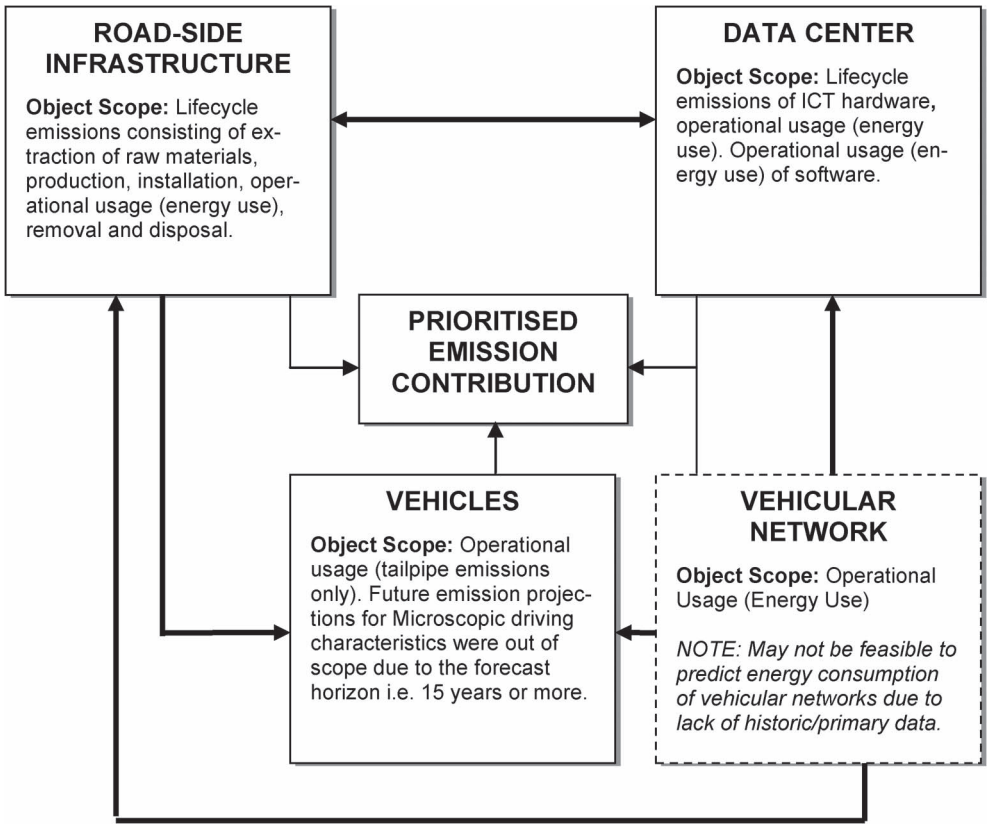

Fig. 3. Environmental scope within an ITS system.

applicable. The U.K. National Transport Model, for instance, uses a combination of ARTEMIS and COPERT IV emission factors. Generally, there was a very good agreement between the shapes of the emission curves in the National Atmospheric Emissions Inventory and the various models tested, but the results varied with vehicle category and pollutant [95]. Rigorous testing was performed, where available, in an attempt to improve the results in several vehicle categories, leading to the conclusion that the current U.K. emission factors should not be changed, but improvements using the models aforementioned were made. Fig. 3 illustrates the desired scope of the environmental evaluation of an ITS scheme at the system level.

V. Forecasting Issues in ITS Technologies

The basic approaches to forecasting include regression and time series methods, which aim to make predictions about likely future events. It is a useful form of research in that it attempts to cope with the rapid changes that are taking place in ITS and predict the impacts of these changes on individuals, organizations, or society. However, it is a method that is fraught with difficulties relating to the complexity of real-world events, the arbitrary nature of future changes, and the lack of knowledge about the future. Researchers cannot build true visions of the future, but only scenarios of possible futures and so impacts under these possible conditions. The performance of regression analysis methods in practice depends on the form of the data-generating process, and how it relates to the regression approach being used. Since the true form of the data-generating process is generally not known, regression analysis often depends to some extent on making assumptions about this process. This is a key issue within the ITS field, in terms of emissions reduction, energy requirements, safety, and cost. There is a limited amount of historical data through real-world trials available. Assumptions in this paper must be carefully formulated or there is a risk that the forecast that the past data are built on may be inaccurate to the point that it becomes invalid. The study area that is to be selected needs to be chosen based upon the quality and availability of historical data. Some uncertainty exists in terms of the future hardware configuration. This depends upon the approach that will be taken by the road network operator and their appropriate technological roadmap. It is acknowledged that the future network within interurban ITS involves four different modes [96]. The prediction of the future system must therefore be carried out with care. TCCs regulate the control of traffic and will also act as a central repository for information. Within the field of ITS, TCCs may be responsible for processing information from different sources, in order to manage the traffic network more efficiently. Each mode can be used in conjunction with another. From a system dynamics approach, these communication modes have been categorized based upon the possible system types.

According to Sterman [97], system dynamics modeling generally follows a five-stage iterative process where the problem is defined (boundary selection). A dynamic hypothesis is generated from the problem, which is then formulated using the modeling diagrams. The model is then tested using

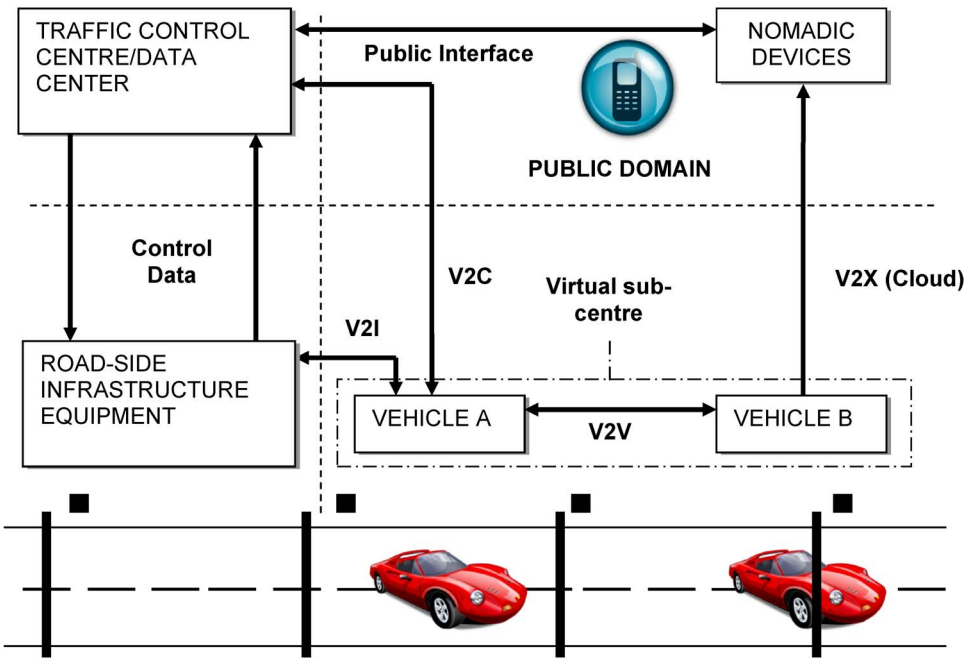

Fig. 4. Communication modes of an ITS System.

existing variables and expected results of dynamic behavior. A policy is then formulated, and evaluation of the system is displayed. The following list represents the possible types of communications, as proposed within the current Cooperative Vehicle-Infrastructure Systems project. The system configuration based upon a system dynamics method is in brackets, as follows:

- V2V: vehicle-to-vehicle (reinforced, closed-loop, endogenous);
- V2I/R: infrastructure/roadside-to-vehicle (reinforced, closed-loop, endogenous);
- V2C: vehicle-to-control center (exogenous, open system);
- V2X: vehicle-to-nomadic devices (exogenous, open system).

The V2X designation implies that this type of services will also be equipped to maintain a connection to the network (even if the driver has left the vehicle) via a mobile device, although this is considered to be public access and will typically involve integration via some form of social network service. Gil-Castineira *et al.* [98] discuss a revolution in dedicated short-range communication (DSRC). DSRC is a selection of one-way or two-way short- to medium-range wireless communication channels that are designed specifically for vehicular use. Protocols and standards are designed to use these specific channels. DSRC can be referred to as a form of telematic because it is used to understand the interactions of technology to provide services, which incorporates sensor wireless devices, vehicle tracking, and online navigation, as well as vehicle operators and road network managers. Fig. 4 illustrates the varying communication types possible within an ITS service. It is important to note (according to Ammoun and Nashashibi [99]) that current communications standards have not been tested within this environment and neither have communications services been proposed. In one future scenario, it may be possible to extend the National Road Telecommunications Services to accommodate the latest and future advances within the communications research domain.

V2V 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 [55], [73], [96], [100]. This form of communication is one of the main topics for debate within the intelligent transport literature and also carries the most uncertainty. For example, it is assumed that V2V communication will be able to operate independently of other infrastructure. This form of communications architecture is looking increasingly feasible from a standpoint of security [101], [102]; the general consensus is that some form of infrastructure will still be required on the roadside to monitor the network. This is because the vehicles are in a constant state of movement. It would prove impossible for a vehicle to possess all data containing all regions; hence, one approach has been to introduce a tagging system, where a vehicle that comes into contact with another vehicle is sent a message about the local area within that current timeframe.

In addition, a sifting method would need to be installed onboard the vehicle, in order to remove data noise, to verify that the data are true and to enforce secure communication. This method would prove more advantageous than having to verify traffic data that are unsuitable due to a different highway or location being assessed, for example. When forecasting future ITS services in this paper, these assumptions must be taken into account. The advantages of the V2V communication system is that it provides notification on hazards and collision avoidance between vehicles [101], [102]. However, according to Rezaei *et al.* [103], tracking vehicles using wireless

communications will be a tough task, due to the vast differences of location and speed of the vehicles. However, Mincheva [104] refers to handling instances of data in a virtual subcenter (VSC), as illustrated in Fig. 4. The VSC aims to manage and distribute data depending on the time and location the connection was made.

Hence, a group of vehicles in a V2V connection that is composed on a network protocol level is known as a VANET cluster. They can communicate, but only within an instance relative to a timeframe at that particular moment and with vehicles that are driving in the same direction. A VSC is maintained via a knowledge-sharing community or vehicular event sharing, as discussed by Delot *et al.* [81] earlier. All the vehicles provide their knowledge into their VSC network, in order to make systems that are independent work together. Data redundancy is therefore approved in this situation since any vehicle can disconnect from the network as they traverse the road network (changing roads, etc.). They are also operated in a decentralized manner but possess a common transport interest [104]. Each vehicle also receives and acts upon these data independently, taking in factors that are unique to the vehicle's status. When traveling alone, vehicles may use other forms of communication to remain updated on current situations. For example, a V2C connection will allow users to maintain updated and basic information about the surrounding area or region. The average lifetime of a VSC instance is short (due to communication ranges, etc.), and a plug-and-play system should allow for an immediate connection and sudden situation awareness.

Vehicle-to-infrastructure communication is a derivative of V2I. Vehicles communicate to the infrastructure displaying various information, which is required to update the traffic network in real time as well as the governance of safety-critical data [105]. Information includes the relaying of current position, speed, etc. Infrastructure devices can include non-road-bearing devices such as GPS and the forthcoming Galileo (EU GPS equivalent). Future technologies, such as platooning, will require new forms of infrastructure that are time sensitive, in order to deliver accurate safety-critical information. Galileo, for instance (which is scheduled for a 2014 activation date), features 30 geographically synchronized satellites that are strategically placed around the Earth's orbit, with a 90% visibility ratio of four satellites in any location on the planet's surface. According to the European Space Agency [106], each satellite has two atomic clocks onboard capable of keeping time to within one billionth of a second per hour. While an analysis of this accuracy leads to the conclusion that it is still inaccurate to sustain the timing of more advanced ITS technologies such as platooning, it is a definite improvement over GPS's current accuracy performance (up to a few meters). This is as the accuracy of the clocks allows a triangulated position of up to 45 cm. Recent breakthroughs in 2010, such as the world's first quantum clock, may allow for these technologies to be implemented in the near future [107]. In addition, Galileo will be fully interoperable with GPS's 24 satellites and serves to improve upon poor polar latitude service by GPS.

According to Dar *et al.* [108], infrastructure-based technologies are equipped with several base stations to relay communication signals over an extended range. One example of this is mobile phone networks with voice data exchange. Due to time-based requirements, they have low latency at the expense of reduced reliability. Mobile networks have similar characteristics; however, the implementation is very different due to the following attributes.

1) They possess low latency because voice data has higher priority than text data, which increases delay.
2) They are not suitable for broadcasting purposes since they support point-to-support communication.
3) The use of mobile networking technology requires operating fees via the network operator.

Despite these drawbacks, however, ITS applications may be powered by existing mobile networks provided that they require moderate delay, long-range communication, and low data rates. V2I communication requirements for ITS applications differ, depending on the service that is required.

Finally, driver behavior and user acceptance, while this communication mode is in operation, should be monitored for more successful adoption [109]. Communications between the vehicle and TCC or regional control center (RCC) sends information including the current position, speed and other variables associated with the management of the traffic network. The literature argues that TCCs are acting as a distributor rather than a communication choice. Mincheva [104] proposes that the future network will maintain a constant communication mode, which is used to transmit "global" information about the region. This form of communication is bidirectional between the vehicle and the RCC. The purpose of this mode is to fill in the data "gaps" when vehicles are traveling alone in isolated conditions (such as B roads, quiet periods, and country access). The type of data transmission will be long range; therefore, the data packets will be small compared to other communication modes. The types of data to be sent include information about the region as well as the tracking of the vehicle, although certain privacy legislation may be violated unless an agreement is made. The advantages of this mode include a constant connection to the control center, regardless of where the vehicle is located as well as low levels of latency. In addition, during an event where safety is at stake, the driver can contact the control center for immediate assistance. The drawbacks to this approach include small data packets and data rate due to the distance and communication mode. V2X deals with the vehicle sending data to nomadic (mobile) devices, which may include mobile phones, moving nodes, and the provision of ICT-based services, in order to maintain management of the traffic network. Gil-Castineira *et al.* [98], [110] discuss the nomadic properties of devices, which would be integrated into a vehicles automotive system. They argue that consumers demand ICT services to be available at the touch of a button; therefore, according to Fensel's [111] Web 3.0 vision (the forthcoming third generation of Internet-based services), information is abstracted from software based around a service-oriented architecture. In other words, the Internet from a transport network view is seen as a *platform* as opposed to an information repository. Devices that are not connected to an ICT system may quickly become outdated and therefore obsolete. Information related

TABLE IV
COMMUNICATION REQUIREMENTS FOR ITS APPLICATIONS

Communication Requirements	ITS Applications					
	Safety Applications				Efficiency Applications	
	Automated Vehicle	Collision Avoidance	Road sign notifications	Incident Management	Traffic Management	Road Monitoring
Communication Mode	V2V/V2I-direct	V2V/V2I-direct	V2I-direct	V2V/V2I-direct	V2I/V2I-direct	V2I/V2I-direct
Directionality	2	1/2	1	1	1/2	1
Latency	Very low	Very low	Low	Low	Low-Medium	Low
Data rate	High	Medium	Medium	Medium	Low-medium	Low-medium
Range	Short	Short	Short	Short-Medium	Short-Medium	Short-Medium
Transmission Mode	1	1	1/3	1/2	1	1/3
Message reliability	High	High	High	High	Medium-High	Medium-High
Message priority	High	High	High	High	Medium	Medium

to incidents and traffic status is constantly being updated; therefore, automotive systems would benefit from a constant connection to Internet-based services to receive safety, navigational, and news updates. This communication type may also allow connection to a pedestrian mobile phone network to alert them of dangerous driving and traffic activity [112]. A successful forecasting of ITS services required an understanding of the technical and also potential cost of the system. While some ITS services, such as ISA, may not require communication with the infrastructure, other more safety-critical systems, such as AHS, require constant information in order to remain active. Table IV shows the individual characteristics of a wireless connection standard compared to the applications that are on offer. The type of system architecture also has a direct impact on the level of embedded emissions and energy requirements. To estimate the sustainability of advanced services such as platooning, for example, the support infrastructure, the datacenter that resides in the TCC, and the vehicular network all need to be taken into account, in order to give an accurate reading. Care must therefore be taken when attempting to estimate the feasibility of future ITS technologies.

VI. CONCLUSION

In this paper a review has been undertaken of the state of the art concerning the evaluation of ITS performance. The goals of the review were to identify the fundamentals and challenges of ITS performance evaluation, highlighting the main differences with established methodologies for standard schemes. These have been used to determine four performance cornerstones for ITS, which are identified as follows: 1) Data Management and IC, 2) Sustainability, 3) Standardization, and 4) Adaptability. The guiding principle was that the framework as a whole should, where possible, draw on best practice in other evaluative tools. This was desirable in order to retain familiarity and ease of use in practice by transport stakeholders.

The research has demonstrated that the task of estimating the performance of ITS is complex. It relies upon a number of actors, including manufacturers, users of the system, and the supporting legislation requirements, such as carbon reduction targets. Methods that support the combination of varying data types from socioeconomic and environmental perspectives, as well as ICT usage in multiple geographical locations such as the datacenter, were needed to capture performance. A summary of the key deficiencies in ITS evaluation frameworks and proposed solutions arising from the research are provided in Table I. While the main focus of the research here has concerned interurban highways, similar challenges in evaluation exist for urban-based ITS. As a result, the findings presented here may also be applied, in order to enhance the evaluation method for urban-based ITS.

REFERENCES

[1] J. He, Z. Zeng, and Z. Li, "Benefit evaluation framework of intelligent transportation systems," *J. Transp. Syst. Eng. Inf. Technol.*, vol. 10, no. 1, pp. 81–87, Feb. 2010.

[2] R. Newman-Askins, L. Ferreira, and J. Bunker, "Intelligent transport systems evaluation: From theory to practice," in *Proc. 21st ARRB/11th REAAA Conf.*, 2003, pp. 1–18.

[3] B. Sultan, "ATM monitoring and evaluation: 4 lane variable mandatory speed limits—12 month report," in *ATM Monitoring and Evaluation*, H. Agency, Ed. Bristol, U.K.: Highways Agency, 2009.

[4] J. Gurínová, *Integrating Intelligent Transport Systems Into the Transportation Planning Process*. Žilina, Slovakia: Univ. Žilina, Faculty of Operation and Economics of Transport and Communications, Department of Road and City Transport, 2005.

[5] E. Bekiaris, A. Stevens, A. Bauer, and M. Wiethoff, "ITS implementation: From impact assessment to policy recommendations," *Res. Transp. Econ.*, vol. 8, pp. 605–637, 2004.

[6] S. Grant-Muller and M. Usher, "Intelligent transport systems: The propensity for environmental and economic benefits," *Technol. Forecasting Social Change*, vol. 82, pp. 149–166, 2013.

[7] A. Amditis, "On balancing costs and benefits in applying VR/VE tools in the intelligent transportation systems sector," *Res. Transp. Econ.*, vol. 8, pp. 483–504, 2004.

[8] J. Barceló, E. Codina, J. Casas, J. L. Ferrer, and D. García, "Microscopic traffic simulation: A tool for the design, analysis and evaluation of intelligent transport systems," *J. Intell. Robot. Syst.*, vol. 41, no. 2/3, pp. 173–203, 2005.

[9] J. L. Su and A. W. Ordys, "Collision avoidance manoeuvre for a vehicle—A practical approach," in *Proc. Inst. Mech. Eng., Part D, J. Autom. Eng.*, 2010, pp. 299–312.
[10] F. Dion, J. S. Oh, and R. Robinson, "Virtual testbed for assessing probe vehicle data in intellidrive systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 3, pp. 635–644, Sep. 2011.
[11] A. Stevens, "The applications and limitations of cost-benefit assessment (CBA) for intelligent transport systems," *Res. Transp. Econ.*, vol. 8, pp. 91–111, 2004.
[12] W. Schade, W. Rothengatter, and T. R. B. Trb, "Improving assessment of transport policies by dynamic cost-benefit analysis," in *Transportation Finance, Economics and Economic Development 2003—Planning and Administration*. Washington, DC, DC, USA: Transportation Research Board National Research Council, 2003, pp. 107–114.
[13] E. Kula and D. Evans, "Dual discounting in cost-benefit analysis for environmental impacts," *Environ. Impact Assess. Rev.*, vol. 31, no. 3, pp. 180–186, Apr. 2011.
[14] J.-C. Thill, G. Rogova, and J. Yan, "Evaluating benefits and costs of intelligent transportation systems elements from a planning perspective," *Res. Transp. Econ.*, vol. 8, pp. 571–603, 2004.
[15] A. Asosheh, S. Nalchigar, and M. Jamporazmey, "Information technology project evaluation: An integrated data envelopment analysis and balanced scorecard approach," *Expert Syst. Appl.*, vol. 37, no. 8, pp. 5931–5938, Aug. 2010.
[16] I. Kaparias *et al.*, "Development and application of an evaluation framework for urban traffic management and intelligent transport systems," *Procedia—Social Behavioral Sci.*, vol. 48, pp. 3102–3112, 2012.
[17] N. Eden *et al.*, "Using key performance indicators for traffic management and intelligent transport systems as a prediction tool," in *Proc. 19th ITS World Congr.*, I. Austria, Ed., Vienna, Austria, 2012, pp. 1–8.
[18] Cabinet Office, *Greening Government ICT*, London, U.K., H. Government, Editor, Cabinet Office, 2009.
[19] K. Christensen, "Green networks: Opportunities and challenges," in *Proc. IEEE 34th Conf. LCN*, 2009, p. 13.
[20] M. T. Riaz, J. M. Gutierrez, and J. M. Pedersen, "Strategies for the next generation green ICT infrastructure," in *Proc. 2nd ISABEL*, 2009, pp. 1–3.
[21] K. Seungdo, K. Hyeon-Kyeong, and K. Hyoung Jun, "Climate change and ICTs," in *Proc. 31st INTELEC*, 2009, pp. 1–4.
[22] A. Shah, T. Christian, C. Patel, C. Bash, and R. Sharma, "Assessing ICT's environmental impact," *Computer*, vol. 42, no. 7, pp. 91–93, Jul. 2009.
[23] L. Ho-Jin and L. Jong-Tae, "Cross-layer congestion control for power efficiency over wireless multihop networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 5274–5278, Nov. 2009.
[24] Cabinet Office, *Greening Government ICT*, London, U.K., H. Government, Editor, Cabinet Office, 2012.
[25] B. Crooks *et al.*, *Raising Awareness of Green IT—The BCS Way*. Swindon, U.K.: British Computer Society (BCS), The Chartered Institute for IT, 2009.
[26] W. Feng, H. Alshaer, and J. M. H. Elmirghani, "Green information and communication technology: Energy efficiency in a motorway model," *IET Commun.*, vol. 4, no. 7, pp. 850–860, Apr. 2010.
[27] Committee on Climate Change, Building a Low Carbon Economy—The UK's Contribution to Tackling Climate Change, 2008.
[28] Mott Macdonald, *M42 ATM Monitoring and Evaluation: Project Summary Report*, Mott Macdonald, Editor, Mott Macdonald, Southhamption, U.K., 2009.
[29] DfT, London Transport Appraisal Guidance 2.1: The Overall Approach—The Steps in the Process 2012, London.
[30] Government, H.G., *Low-carbon transition plan: National strategy for climate and energy*, 2009, Department of Energy and Climate Change, London.
[31] A. Sentance, "Developing transport infrastructure for the low carbon society," *Oxford Rev. Econ. Policy*, vol. 25, no. 3, pp. 391–410, 2009.
[32] J. King, *The King Review of Low Carbon Cars, Part 1: The Potential for CO_2 reduction*. London, U.K.: HM Treasury, 2007.
[33] R. E. Eddington, *The Eddington Transport Study—Transport's Role in Sustaining the UK's Productivity and Competitiveness*. London, U.K.: HM Treasury and Department for Transport, 2006.
[34] I. Patey, J. Conquest, and A. Holt, "Assessing carbon balance of intelligent transport schemes," *Proc. ICE-Eng. Sustainability*, vol. 161, no. 3, pp. 181–184, Sep. 2008.
[35] B. Kolosz, S. Grant-Muller, and K. Djemame, "Modelling uncertainty in the sustainability of intelligent transport systems for highways using probabilistic data fusion," *Environ. Modelling Softw.*, vol. 49, pp. 78–97, Nov. 2013.
[36] B. W. Kolosz, S. M. Grant-Muller, and K. Djemame, "A macroscopic forecasting framework for estimating socioeconomic and environmental performance of intelligent transport highways," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 2, pp. 723–736, Apr. 2014.
[37] H. L. Vu, S. Chan, and L. Andrew, "Performance analysis of best-effort service in saturated IEEE 802.16 networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 460–472, Jan. 2010.
[38] U. Žilina, "Present and future challenges of ICT for intelligent transportation technologies and services," in *Proc. 1ST International Conf. Wireless Commun. Veh. Technol. Inf. Theory Aerosp. Electron. Syst. Technol.*, 2009, pp. 112–115.
[39] E. Valsera-Naranjo, A. Sumper, P. Lloret-Gallego, R. Villafafila-Robles, and A. Sudria-Andreu, "Electrical vehicles: State of art and issues for their connection to the network," in *Proc. 10th Int. Conf. Electr. Power Quality Utilisation*, 2009, pp. 1–3.
[40] Y. Tarte, A. Amanna, and C. Okwudiafor, "Experimental testbed for investigating IEEE 802.11 handoff in vehicular environment," in *Proc. IEEE SoutheastCon*, 2010, pp. 222–225.
[41] S. Shladover, "Automated vehicles for highway operations (automated highway systems)," *Proc. Institution Mech. Eng., Part I, J. Syst. Control Eng.*, vol. 219, no. 1, pp. 53–75, Feb. 2005.
[42] H. Reijmers, M. Ozguzel, and R. Prasad, "Performance analysis of a communication network for intelligent transport systems," in *Proc. Conjunction Pacific Rim TransTech Conf. 6th Int. VNIS Conf.*, 1995, pp. 529–534.
[43] M. Raya and J. Hubaux, *The Security of Vehicular Ad Hoc Networks*. New York, NY, USA: ACM, 2005.
[44] Commission for Integrated Transport, Transport and Climate Change, 2007.
[45] S. Brown, D. Pyke, and P. Steenhof, "Electric vehicles: The role and importance of standards in an emerging market," *Energy Policy*, vol. 38, no. 7, pp. 3797–3806, Jul. 2010.
[46] S. Ruth, "Green IT more than a three percent solution?" *IEEE Internet Comput.*, vol. 13, no. 4, pp. 74–78, Jul./Aug. 2009.
[47] D. Spanos and R. Murray, "Robust connectivity of networked vehicles," in *Proc. 43rd IEEE Conf. Decision Control*, 1994, pp. 2893–2898.
[48] A. Tuominen and T. Ahlqvist, "Is the transport system becoming ubiquitous? Socio-technical roadmapping as a tool for integrating the development of transport policies and intelligent transport systems and services in Finland," *Technological Forecasting Social Change*, vol. 77, no. 1, pp. 120–134, Jan. 2010.
[49] S. Vlassenroot, K. Brookhuis, V. Marchau, and F. Witlox, "Towards defining a unified concept for the acceptability of Intelligent Transport Systems (ITS): A conceptual analysis based on the case of Intelligent Speed Adaptation (ISA)," *Transp. Res. Part F, Traffic Psychology Behaviour*, vol. 13, no. 3, pp. 164–178, May 2010.
[50] "Standardisation Activities for Intelligent Transport Systems, in ITU-T Technology Watch Report 8," Geneva, Switzerland, 2008.
[51] Highways Agency, ITS Standards Tracking Database. ITS Radar International—Standards, 2010. [Online]. Available: http://www.itsradarinternational.info/Standards/
[52] J. Traub, *Information-Based Complexity*. Hoboken, NJ, USA: Wiley, 2003.
[53] R. L. French, "The IEEE and ITS," *IEEE Intell. Syst.*, vol. 14, no. 6, pp. 75–77, Nov. 1999.
[54] C.-J. Huang, Y.-J. Chen, I. F. Chen, and T.-H. Wu, "An intelligent infotainment dissemination scheme for heterogeneous vehicular networks," *Expert Syst. Appl.*, vol. 36, no. 10, pp. 12472–12479, Dec. 2009.
[55] A. Boukerche, H. Oliveira, E. Nakamura, and A. Loureiro, "Vehicular ad hoc networks: A new challenge for localization-based systems," *Comput. Commun.*, vol. 31, no. 12, pp. 2838–2849, Jul. 2008.
[56] W.-H. Lee, S.-S. Tseng, and W.-Y. Shieh, "Collaborative real-time traffic information generation and sharing framework for the intelligent transportation system," *Inf. Sci.*, vol. 180, no. 1, pp. 62–70, Jan. 2010.
[57] R. Meier, A. Harrington, and V. Cahill, "A framework for integrating existing and novel intelligent transportation systems," in *Proc. IEEE Intell. Transp. Syst.*, 2005, pp. 154–159.
[58] J. Zhao and G. Cao, "VADD: Vehicle-assisted data delivery in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1910–1922, May 2008.
[59] B. McQueen and J. McQueen, *Intelligent Transportation Systems Architectures*. Norwood, MA, USA: Artech House Publishers, 1999.
[60] J. Zhang *et al.*, "Data-driven intelligent transportation systems: A survey," *IEEE Trans. Transp. Syst.*, vol. 12, no. 4, pp. 1624–1639, Dec. 2011.
[61] M. Zargayouna, F. Balbo, and J. Trassy, "Agent information server: A middleware for traveler information," in *Lecture Notes Comput. Sci.*, 2006, vol. 3963, pp. 14–28.

[62] B. Parno and A. Perrig, "Challenges in Securing Vehicular Networks," in *Proc. Workshop HotNets-IV*, 2005, pp. 1–6.

[63] F. Picconi, N. Ravi, M. Gruteser, and L. Iftode, "Probabilistic validation of aggregated data in vehicular ad-hoc networks," in *Proc. 3rd Int. Workshop Veh. Ad Hoc Netw.*, 2006, pp. 76–85.

[64] L. Nazaryan, E. Panaousis, and C. Politis, "End-to-end security protection," *IEEE Veh. Technol. Mag.*, vol. 5, no. 1, pp. 85–90, Mar. 2010.

[65] P. Papadimitratos, A. La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 84–95, Nov. 2009.

[66] P. Papadimitratos, V. Gligor, and J. Hubaux, "Securing vehicular communications—Assumptions, requirements, and principles," in *Proc. Workshop ESCAR*, 2006, pp. 5–14.

[67] H. Xiong, Z. G. Qin, and F. G. Li, "Secure vehicle-to-roadside communication protocol using certificate-based cryptosystem," *IETE Tech. Rev.*, vol. 27, no. 3, pp. 214–219, May 2010.

[68] R. G. White *et al.*, "Privacy and scalability analysis of vehicular combinatorial certificate schemes," in *Proc. 6th IEEE Conf. CCNC*, 2009, pp. 624–628.

[69] T. W. Chim, S. M. Yiu, L. C. K. Hui, and V. O. K. Li, "SPECS: Secure and privacy enhancing communications schemes for VANETs," *Ad Hoc Netw.*, vol. 9, no. 2, pp. 189–203, Mar. 2010.

[70] Z. Ma, F. Kargl, and M. Weber, "Measuring long-term location privacy in vehicular communication systems," *Comput. Commun.*, vol. 33, no. 12, pp. 1414–1427, Mar. 2010.

[71] M. Torrent-Moreno, "Inter-vehicle communications: Assessing information dissemination under safety constraints," in *Proc. Annu. Conf. WONS*, 2007, pp. 59–64.

[72] B. S. Gukhool and S. Cherkaoui, "Handoff in IEEE 802.11p-based vehicular networks," in *Proc. IFIP Int. Conf. WONS*, 2009, pp. 1–5.

[73] M. Bell, "Policy issues for the future intelligent road transport infrastructure," *IEEE Proc. Intell. Transp. Syst.*, vol. 153, no. 2, pp. 147–155, Jun. 2006.

[74] I. Cassias and A. Kun, "Vehicle telematics: A literature review," Univ. New Hampshire, Durham, NH, USA, ECE.P54.2007.9, Oct. 30, 2007.

[75] B. Drilo, D. Saric, and R. Filjar, "The role of telecommunications in development of new-generation Intelligent Transport Systems," in *Proc. 1st Int. Conf. Wireless Commun., Veh. Technol., Inf. Theory Aerosp. Electron. Syst. Technol., Wireless VITAE*, 2009, pp. 125–127.

[76] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter, "MDDV: A mobility-centric data dissemination algorithm for vehicular networks," in *Proc. 1st ACM Int. Workshop Veh. Ad Hoc Netw.*, 2004, pp. 47–56.

[77] Y. Elhillali *et al.*, "Enhanced high data rate communication system using embedded cooperative radar for intelligent transports systems," *Transp. Res. Part C, Emerging Technol.*, vol. 18, no. 3, pp. 429–439, Jun. 2010.

[78] N.-E. E. Faouzi, H. Leung, and A. Kurian, "Data fusion in intelligent transportation systems: Progress and challenges—A survey," *Inf. Fusion*, vol. 12, no. 1, pp. 4–10, Jan. 2011.

[79] E. Moschetta, R. S. Antunes, and M. P. Barcellos, "Flexible and secure service discovery in ubiquitous computing," *J. Netw. Comput. Appl.*, vol. 33, no. 2, pp. 128–140, Mar. 2010.

[80] L. Galluccio, A. Leonardi, A. Matera, and S. Palazzo, "Service capacity in vehicular networks: A resource dissemination analysis," *Ad Hoc Netw.*, vol. 5, no. 8, pp. 1272–1283, Nov. 2007.

[81] T. Delot, N. Cenerario, and S. Ilarri, "Vehicular event sharing with a mobile peer-to-peer architecture," *Transp. Res. Part C, Emerging Technol.*, vol. 18, no. 4, pp. 584–598, Aug. 2010.

[82] C. K. Lo, S. Vishwanath, and R. W. Heath, "An energy-based comparison of long-hop and short-hop routing in MIMO networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 394–405, Jan. 2010.

[83] C.-L. Lin, M.-S. Hsieh, and G.-H. Tzeng, "Evaluating vehicle telematics system by using a novel MCDM techniques with dependence and feedback," *Expert Syst. Appl.*, vol. 37, no. 10, pp. 6723–6736, Oct. 2010.

[84] M. Ferreira and P. M. d'Orey, "On the impact of virtual traffic lights on carbon emissions mitigation," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 284–295, Mar. 2012.

[85] L. Int Panis, S. Broekx, and R. Liu, "Modelling instantaneous traffic emission and the influence of traffic speed limits," *Sci. Total Environ.*, vol. 371, no. 1–3, pp. 270–285, Dec. 2006.

[86] EC, *MEET—Methodology for Calculating Transport Emissions and Energy Consumption*, 1999, Office for Official Publications of the European Communities: Luxembourg.

[87] R. Smit, L. Ntziachristos, and P. Boulter, "Validation of road vehicle and traffic emission models—A review and meta-analysis," *Atmospheric Environ.*, vol. 44, no. 25, pp. 2943–2953, Aug. 2010.

[88] M. André, "The ARTEMIS European driving cycles for measuring car pollutant emissions," *Sci. Total Environ.*, vol. 334/335, no. 0, pp. 73–84, Dec. 2004.

[89] Y. Ding and H. Rakha, "Trip-based explanatory variables for estimating vehicle fuel consumption and emission rates," *Water, Air Soil Pollution: Focus*, vol. 2, no. 5/6, pp. 61–77, Aug. 2002.

[90] A. Cappiello, I. Chabini, E. K. Nam, A. Lue, and M. Abou Zeid, "A statistical model of vehicle emissions and fuel consumption," in *Proc. IEEE 5th Int. Conf. Intell. Transp. Syst.*, 2002, pp. 801–809.

[91] R. Akcelik and M. Besley, "Operating cost, fuel consumption, and emission models in aaSIDRA and aaMOTION," in *Proc. 25th CAITR University of South Australia*, Adelaide, SA, Australia, 2003, pp. 1–15.

[92] F. An, M. Barth, J. Norbeck, and M. Ross, "Development of comprehensive modal emissions model: Operating under hot-stabilized conditions," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1587, no. 1, pp. 52–62, 1997.

[93] K. Ahn, H. Rakha, A. Trani, and M. Van Aerde, "Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels," *J. Transp. Eng.*, vol. 128, no. 2, pp. 182–190, Mar. 2002.

[94] M. Barth, S. Mandava, K. Boriboonsomsin, and X. Haitao, "Dynamic ECO-driving for arterial corridors," in *Proc. IEEE FISTS*, 2011, pp. 182–188.

[95] P. Boulter, T. Barlow, I. McCrae, and S. Latham, "Emission factors 2009: Final Summary Report, TRL, Editor," TRL Limited, Berkshire, U.K., PPR361, 2009.

[96] S. Fuchs and D. Bankosegger, "Developing value networks for I2V cooperative services—An Austrian example," *IET Intell. Transp. Syst.*, vol. 3, no. 2, pp. 216–224, Jun. 2009.

[97] J. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*. New York, NY, USA: Irwin/McGraw-Hill, 2000.

[98] F. Gil-Castineira, D. Chaves-Dieguez, and F. J. Gonzalez-Castano, "Integration of nomadic devices with automotive user interfaces," *IEEE Trans. Consum. Electron.*, vol. 55, no. 1, pp. 34–41, Feb. 2009.

[99] S. Ammoun and F. Nashashibi, "Design and efficiency measurement of cooperative driver assistance system based on wireless communication devices," *Transp. Res. Part C, Emerging Technol.*, vol. 18, no. 3, pp. 408–428, Jun. 2010.

[100] O. Hamouda, M. Kaaniche, E. M. Moller, J. G. Rasmussen, and H. P. Schwefel, "Connectivity dynamics in vehicular freeway scenarios," in *Proc. GIIS*, 2009, pp. 1–8.

[101] J. Santa, R. Toledo-Moreo, M. A. Zamora-Izquierdo, B. Úbeda, and A. F. Gómez-Skarmeta, "An analysis of communication and navigation issues in collision avoidance support systems," *Transp. Res. Part C, Emerging Technol.*, vol. 18, no. 3, pp. 351–366, Jun. 2010.

[102] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: Fair transmit power control for safety-critical information," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3684–3703, Sep. 2009.

[103] S. Rezaei, R. Sengupta, H. Krishnan, X. Guan, and R. Bhatia, "Tracking the position of neighboring vehicles using wireless communications," *Transp. Res. Part C, Emerging Technol.*, vol. 18, no. 3, pp. 335–350, Jun. 2010.

[104] E. A. Mincheva, "Intelligent vehicle clusters (Inside Com2React project)," *IET Intell. Transp. Syst.*, vol. 3, no. 2, pp. 206–215, Jun. 2009.

[105] H. Cai and Y. Lin, "A roadside ITS data bus prototype for intelligent highways," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 2, pp. 344–348, Jun. 2008.

[106] European Space Agency, Galileo Navigation, [cited 2010 28/08/10], 2010. [Online]. Available: http://www.esa.int/esaNA/SEMTK50DU8E_galileo_0.html

[107] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, "Frequency comparison of two high-accuracy Al+ optical clocks," *Phys. Rev. Lett.*, vol. 104, no. 7, pp. 070802-1–070802-4, Feb. 2010.

[108] K. Dar, M. Bakhouya, J. Gaber, M. Wack, and P. Lorenz, "Wireless communication technologies for ITS applications," *IEEE Commun. Mag.*, vol. 48, no. 5, pp. 156–162, May 2010.

[109] M. Böhm, S. Fuchs, R. Pfliegl, and R. Kolbl, "Driver behavior and user acceptance of cooperative systems based on infrastructure-to-vehicle communication," in *Proc. Transp. Res. Rec.*, 2009, pp. 136–144.

[110] F. Gil-Castineira, D. Chaves-Dieguez, J. Gonzalez-Castano, and E. Costa-Montenegro, "Integration of web 2.0 with automotive user interfaces via nomadic devices," in *Proc. IEEE Int. Conf. Consum. Electron.*, 2009, pp. 1–12.

[111] P. D. Fensel, "ServiceWeb 3.0," in *Proc. IEEE/WIC/ACM Int. Conf. IAT*, 2007, p. 22.

[112] K. David and A. Flach, "CAR-2-X and pedestrian safety," *IEEE Veh. Technol. Mag.*, vol. 5, no. 1, pp. 70–76, Mar. 2010.

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