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'Sustainability assessment approaches for Intelligent Transport Systems: The state of the art'

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Abstract

The appraisal of ITS systems has become increasingly important in order to capture their full range of potential impacts. The goal of this paper is therefore to assess the appropriateness of conventional transport appraisal models and tools for this task, particularly in reflecting the environmental and socio-economic impacts of ITS. These include the most common Environmental Systems Analysis tools (ESAT), which incorporate international standards and are of considerable importance in indicating sustainability. A review of how emerging methods relate to the goal of a successful transition to a low carbon future is reported, based on the literature. The appraisal of ITS is inherently uncertain due to the decentralised nature of Information Communication Technology (ICT), therefore a range of methods to capture this aspect are reviewed. The models, weights and methods are analysed concerning their ability to estimate sustainability performance, given the numerous configurations of ubiquitous technology that may comprise ITS services. Weighting methods are important in reflecting perceptions of how sustainability should be assessed. These can be incorporated by identifying, classifying and selecting one or more ESAT's based upon their suitability for a particular application. Finally, recommendations are given on which tools can be integrated to more comprehensively reflect the performance of ITS.

Keywords:
Intelligent Transport Systems, Transport appraisal, Uncertainty, Environmental impact assessment, Sustainability.

1 Introduction

The gradual integration of technology into roadside infrastructure has contributed to substantial savings from environmental and socio-economic perspectives. The literature [1-5] describes Intelligent Transport Systems (or ITS) as an 'umbrella' term which takes into account the application of ICT based systems and transport to provide 'intelligent' services. The intelligence of ITS is derived from the ability to assist in, or make decisions based upon, a pro-reactive response to the environment. A variety of current ITS systems allow increased navigation, alertness and response to critical and non-critical scenarios [6-8]. Examples of current ITS include Variable Message Signs (VMS) where messages are displayed on overhead gantries. VMS provide general traffic information including route Estimated Time of Arrival (ETA) and weather patterns within the route, alerting drivers of serious incidents such as collisions and traffic congestion. Other examples of ITS include toll collection via an electronic tag installed within the car to pay for road use and parking measures [9, 10].

The introduction of ICT has enabled ITS technologies such as Active Traffic Management (ATM) to reduce congestion through remote communication using equipment such as variable message signs and Closed Circuit Television (CCTV). Active Traffic Management consists of the dynamic control and marshalling of the transport network under severe congestion and on more recent implementations, the use of temporary shoulder running so that the hard shoulder can be used as a running lane during periods of extreme congestion. The components of ATM include physical infrastructure such as overhead gantries, surveillance and sensor networks [11]. However the ICT element has not been central to many non-ITS schemes and therefore a new approach to assessing the sustainability of ITS is needed. The term 'sustainability' has been widely applied and given many definitions. Recent literature has separated the sustainability paradigm into three key dimensions: environmental, social and economic, although there are still differences in the use of the term [12-14]. Wallis et al [15] argue that since the release of Agenda 21 in 1992 a great deal of effort at the regional, national and global scales has been given to the development of indicators for sustainability [16]. In addition, there are no universal indicators for sustainability that are supported by theory, data collection or policy governance, particularly towards Intelligent Transport. This is due to ambiguity within the definition of sustainability and has led to the production of a large body of work which crosses multi-disciplinary boundaries in terms of the applications assessed. Sustainability indicator sets are currently formed by generic social and economic indicators brought together from matrices that focus on environmental reporting [17-19]. These indicators often fall short of the level of information needed to support transport project appraisal under increasing pressure to reduce the threat of climate change [20-22]. The implementation of ITS could offer promising rewards in the form of reduced emissions and improved safety. It may also relieve some of the current pressure to transform the technology within the vehicles themselves but which (at this moment in time) is proceeding at a slow pace due to several policy barriers, despite rapid improvements in technology [23, 24].

The aim of this paper is to review current transport appraisal methods and their use in assessing ITS technologies. It should be noted that the focus of the paper is on inter-urban ITS including fixed based infrastructure such as Active Traffic Management as well as vehicular based driver assisted systems. The paper begins with a critique of contemporary environmental and socio-economic models, focusing on transport, the ICT field and ITS where available. The second part of the paper illustrates the relational attributes between the environmental and socio-economic models so that a common understanding of what each method contributes to the assessment of sustainability is formed. From this, a review of the sustainability literature has contributed to the design of a proposed framework to assess the sustainability of ITS services against current and future target emissions. This can form the basis for measuring sustainability performance in current and forthcoming ITS technologies and services. Methods were selected based upon their individual features and so that those with most weaknesses in terms of assessing ITS could be discounted. The chosen methods are designed to stimulate debate within the transport community so that further recommendations can be given to enhance the sustainability of ICT based Intelligent Transport systems.

2 Established transport appraisal methods

In the sustainability assessment field, macro-economic, social-economic and energy based models are all used to explore energy demand and carbon reduction within the transport sector [25]. According to the literature [26-30] these tools bear significant weight within the sustainable transport arena and include, but not limited to:

- Cost Benefit Analysis (CBA) and Cost Effectiveness Analysis (CEA)
- Multi-Criteria Analysis (MCA)
- Environmental Impact Assessment (EIA) and Environmental Risk Assessment (ERA)
- Life Cycle Assessment (LCA) and Life-cycle Cost Analysis (LCCA)

Environmental System Analysis Tools (ESAT's) are designed to assess environmental impacts of the systems studied while socio-economic models are designed to assess the monetary implications of a project, social aspects illustrate the impacts of the ITS technology from the consumers' perspective. Most of the tools feature their own metrics and therefore a long list of sustainability impact factors may be available [31] .

2.1 Cost-Benefit Analysis and Cost effectiveness analysis

CBA (and its discounting method) has a central role in determining the feasibility of current and future road transport projects. Sentance [32] argues that to create and maintain a low carbon policy it is necessary to implement emissions trading (ETS) and taxation where both mechanisms have individual benefits, however, not all parties may perceive the mechanisms as a positive measure. It is also recommended that they be suited to a particular region or sector, therefore the literature recommends a sectoral approach [33, 34]. CBA has attracted some criticism due to its one-dimensional monetary valuation judgments, and to a lesser extent, the role of the discount rate or the appraisal period to be used [35, 36]. The literature identifies a number of CBA studies applied to current and anticipated ITS systems (see Table 1).

Review of CBA/CEA applied to ITS			
ITS Technology	**Country/Region of Study**	**Literature**	**Number of studies**
Active Traffic Management *incl. Variable Message Signs*	France	[37]	
	USA	[38]	
	Canada	[39]	5
	Finland	[40]	
	UK	[41]	
Automated Highway System	Generalised	[42]	
	Germany/Japan	[43, 44]	4
	UK	[41]	
Advanced Driver Assisted Systems	Norway	[45]	
	UK/USA	[46, 47]	6
	UK	[41, 48, 49]	
Travel Information System	USA	[50]	
Combined/Strategic Analysis and Frameworks	UK	[51]	
	EU	[52, 53]	6
	USA	[54]	
	N/A	[55]	

Table 1: - Studies of CBA applied to ITS

According to Stevens [55], CBA offers various advantages in measuring the sustainability performance of ITS. It uses established economic principles to assign values and is therefore able to reflect whether the investment is worthwhile to society from a holistic perspective. It may also be required in order to secure public or private sector funding. In the current political climate, this may result in prioritisation of environmentally sustainable

ITS. Modifications to the established CBA methodology may allow the measurement of environmental ITS performance to become a reality. Stevens [55] explores the typical methodology for evaluating ITS projects (see in Figure 1).

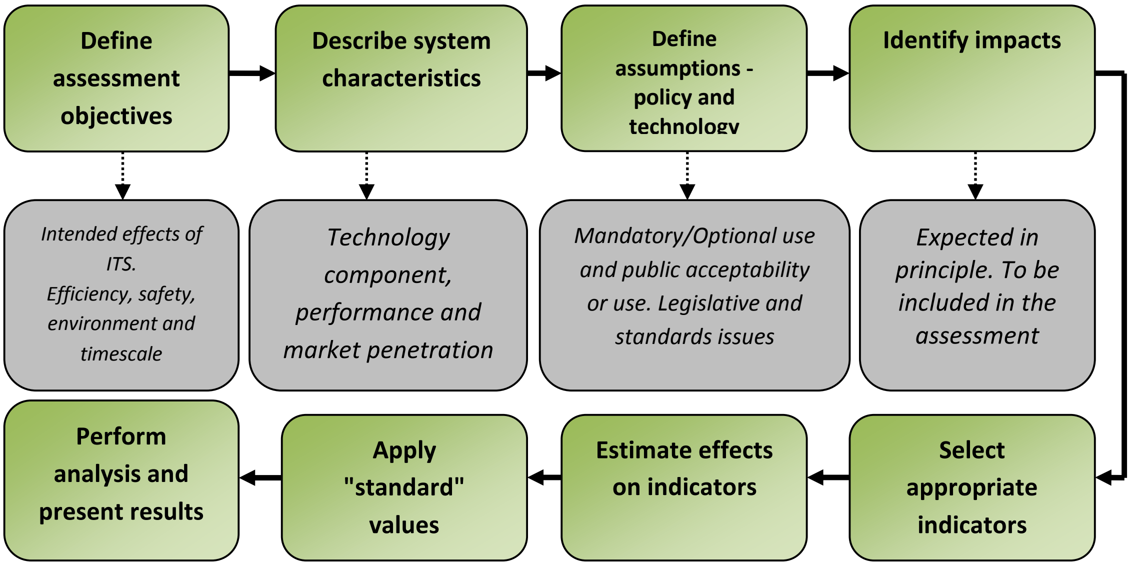

Figure 1: - Typical ITS Cost Benefit Methodology (Source: 55)

Earlier notable studies took an approach based on performance indicators for ITS. These included the analysis of ITS performance in the EU FP5 funded CITY PIONEERS, which developed project guidance for local regions in implementing ITS applications [56] . The introduction of simplistic ITS performance indicators were also the goal of the EU funded MAESTRO project [52]. The Maestro guidelines focused upon assessing new technologies and services from theory to implementation. More recently, Lai et al [57] conducted a CBA for accident reduction and fuel consumption for Intelligent Speed Adaptation (ISA). Intelligent Speed Adaptation (ISA), also known as Intelligent Speed Assistance, Speed Alert, and Intelligent Speed Authority, is any system that constantly monitors vehicle speed and the local or safe speed limit on a road and implements an action when the vehicle is detected to be exceeding the speed limit [57-59]. This can be done through an advisory system, where the driver is warned, or through an intervention system where the driving systems of the vehicle are controlled automatically to reduce the vehicle's speed. The study was based on two independent market penetration scenarios: market driven and authority driven. Overall, the cost benefit ratio for the market scenario to 2070 was 3.4, whilst the corresponding figure for the authority scenario was 7.4. Stevens [55] argues that for any measures of performance, validity, reliability and sensitivity all play a key role for the measurement of successful applications and services.

CBA, as a sole ESAT tool, has disadvantages for ITS service appraisal in line with issues raised within the literature. Firstly, CBA is traditionally calibrated based upon past projects and due to the lack of historical data, the accuracy of the cost benefit assessment may suffer and an expert judgment given instead. Due to time, scope and budget constraints the appraisal may not be performed successfully, jeopardising historical data accuracy for future projects. Dis-benefits (such as climate change) may not be reported satisfactorily, although Stevens [55] argues that publicising project side effects such as pollution may compromise the readiness and support of future transport projects. The counter-argument is that environmental transparency is high on the political agenda, therefore the impact on the environment should be documented thoroughly. Valuation outcomes such as willingness to pay (or accept) are aggregated figures and based upon values such as income. The methods used to value impacts (stated preference and hedonic pricing) may not be completely adequate and the knowledge base to estimate longer-term impacts may be missing. Policy judgements are therefore required and may usher expert opinion. The valuation of environmental impacts over a long period may not be feasible using CBA alone as qualitative aspects such as social, safety and welfare cannot be processed through this methodology without modification to the discounting method. The main disadvantage of CBA is the ignorance of distributions and equity effects and to a lesser extent it's monetary/ WPT focus.

Recent research suggests approaches such as dual and declining discounting may allow such issues to be addressed in future [60, 61].

2.2 Multi-Criteria Analysis

Other suitable tools to assess ITS sustainability include Multi-Criteria Analysis (MCA) which dominates the Multi-Criteria Decision Making (MCDM) approaches. Dodgson et al [27] refers to MCA as a set of pre-defined approaches that offer a variety of solutions compared to CBA and comprise a unified set of techniques. Key differences include CBA being based on economic efficiency criteria (e.g. Net Present Value), while MCA incorporates other types of criteria, e.g. distributional, equity and ecological. In CBA, alternatives are evaluated by monetised criteria, as opposed to MCA which is not based exclusively on monetary valuations. Finally a CBA only supports quantitative data while MCA may use both quantitative and qualitative data.

A limited number of studies have been conducted on ITS using MCA methods. Most have focused on a combined strategic analysis of supplier choice, technology selection and planning [62-64]. Ghaeli et al [65] proposed an integrated project portfolio selection model using the Analytical Hierarchy Process (AHP) and proven concepts used for portfolio selection in the finance discipline. AHP is a structured technique for organizing and analysing complex decisions. Based on mathematics and psychology, it was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then [66]. This methodology facilitates decision making by integrating both the risk and the value of projects. Agusdinata et al [67] presented an innovative MCA approach based on exploratory modelling to handle uncertainties surrounding Intelligent Speed Adaptation policymaking. This approach uses computational experiments to explore the multiple outcomes of ISA policies (safety, emissions, throughput and cost) across a range of future demand scenarios, functional relationships for performance criteria and user responses to ISA.

Methods such as Analytical Network Process (ANP) can assist in prioritising ITS services against alternatives. The analytic network process (ANP) is a more general form of the analytic hierarchy process (AHP) used in multi-criteria decision analysis. AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network. Both then use a system of pairwise comparisons to measure the weights of the components of the structure and finally to rank the alternatives in the decision. Jung et al [62] prioritized six ITS services using ANP, which considers mutual dependence between the evaluation items and alternatives. AHP is a one-way process that does not consider the independence of feedback from the services. According to the results of their super decisions ratings, the Regional Traffic Information Centre System was chosen to be the top priority project followed by the Urban Arterial Incident Management System.

Khademi et al [64] illustrated 33 ITS user services through a hybrid model of the disjunctive satisfying method (DSM) and ANP. The DSM reduces the problem size by excluding inappropriate user services while the ANP establishes overall relative preferences for selected user services by considering various inner dependencies, interdependencies and mutual effects among the elements. Electronic payment, travel demand management and traffic control user services were proposed as the best alternatives for the problem in a developing country.

Lasdon and Machemehl [68] used the Elimination and Choice Expressing Reality (ELECTRE) method to compare various ITS deployments. A modified ELECTRE-I method was developed to compare a number of ITS alternatives against multiple objectives. By varying the weighting scheme to favour different criteria and performing a sensitivity analysis, a nominated alternative was identified.

It is possible to enhance methodological development for potential ITS appraisal frameworks using MCA, which is perceived to deal with many of the deficiencies of CBA (or Distributional CBA). However, to consider the numerous stakeholders involved within ITS and to manage the social, economic and environmental perspectives this method would have to use a two-tiered priority system, weighting criteria using a performance ranking system. Experts would rate the criteria and provide anticipated targets. Weighted priorities could then be given for each pillar of sustainability as well as the individual criteria. Experts' utility values could determine if emissions are improving or worseningand whether targets have been achieved. However, another method may be needed in order to handle the identification, normalisation and ranking of such targets.

2.3 Environmental Impact Assessment and Environmental Risk Assessment

Environmental Impact Assessment (EIA) was initially introduced to overcome some limitations of CBA, including subjectivity, conflict and uncertainty [69]. These limitations are particularly evident in the case of transport infrastructure. While both social cost and generalized travel cost must be considered, these may include intangibles such as social damage from air pollution or risk to life that can be difficult to monetise, plus a monetary criterion is not always socially acceptable [69]. According to Pölönen et al [70] EIA can be described as a preventive environmental policy and management tool that has been used worldwide to assess the environmental effects of projects systematically and comprehensively. To the best of the authors knowledge, EIA/ERA have not been conducted on ITS as most schemes do not require significant change in land use. This is largely due to the characteristics of ITS as systems which can be controlled remotely as opposed to physical infrastructure being required for traffic guidance. A typical EIA may struggle to estimate the performance of ubiquitous systems due to its focus on a localised area, while ERA focuses on damage assessment and mitigation. Damage by ITS is presumed to be marginal compared with widening a highway, for example. Active Traffic Management requires little additional land-use as its goal is to utilise existing infrastructure. Any manufacturing is undertaken off-site with the changes in vehicle emissions viewed as a marginal by-product. The datacenter is also off-site with its own performance specification. As the traditional EIA/ERA relies on historical data it would therefore be unfeasible to adopt this approach for ITS assessment given the implementation and consequent benefits of ITS require no substantial changes to land use. Although this approach may be used to assess post implementation criteria such as noise, it is only undertaken in the planning and post-implementation phases of transport appraisal. As a result this type of approach is largely inappropriate for sole use in assessing the likely future operational performance of an ITS scheme.

2.4 Life Cycle Assessment and Life Cycle Cost Analysis

Life cycle assessment (LCA) was established in the 1990's, slowly gathering international recognition and popularity thereafter [26, 71, 72]. It was later subject to some criticism by the academic community due to the resource intensive data collection and computation needed. It has since improved substantially, including recalibration and harmonisation within the methodology which lead to clearer outcomes. The literature highlights many different approaches, although two dominate i.e. 'attributional' and 'consequential' LCA [26, 73, 74]. The former is essentially a point estimate in time and is calculated using historical data. The consequential approach considers marginal and major changes to a system, whether this change occurred in the past, present or the future [75-77]. The most appropriate approach largely depends on the product or service under assessment. Once the approach is selected there is the option to perform either a simplified or full LCA. The former is affordable and quick to calculate, whilst the latter increases accuracy at the cost of intensive data collection. Using a process based LCA, measurements of ITS road infrastructure must also provide similar accuracy as an estimation of emissions from a vehicles power source. The main advantage of this approach is its simplicity and ease of use. Disadvantages include input 'black spots' where data may be missing or unavailable. Very complex manufacturing processes may therefore lose much in the interpretation of the lifecycle results.

To the best of the authors' knowledge, to date few LCA studies on ITS schemes have been published. One exception is Kolosz et al [78, 79] who integrated LCA and MCA with a probabilistic data method (Dempster-Shafer). The results indicated that datacenter emissions required significant improvement to ensure the ITS lifecycle was sustainable. Several studies have taken the microscopic perspective, focusing on renewable energy [74], material replacement [80], vehicle emissions and ICT products [28]. Within the transport sector, studies have focused on traffic throughput [81, 82], Input-Output models for economic supply and demand, alternative fuels [83] and vehicle technologies [84]. In terms of scope, the Ecoinvent database also includes logistics inventory data for freight transport [82]. According to Higgs et al [28] considerable efforts have been made to define the whole lifecycle of energy production and CO_2 impact of ICT as well as the materials used in the manufacturing process. The main issue is a lack of inventory data for high purity or speciality chemicals [82, 85]. ICT systems may include roadside infrastructure for displaying messages, datacenters for storing traffic information, traffic control systems and general telecommunication services such as surveillance and route guidance. Determining the energy and carbon emissions while the product is in use is challenging due to the many equipment configurations possible [86, 87]. This is important, as an Economic Input-Output LCA often concludes that embedded energy contributes a larger portion of lifecycle energy and CO_2 impact compared to process based LCA's, which argue that product use is the largest contributor. Calculating the levels of energy and CO_2 within the IT supply chain is even more complex. Some projects have attempted to introduce their own methodologies for assessing the change of energy requirements in vehicles. For example, AMITRAN "CO2 Assessment Methodology for ICT in Transport" – has defined a methodology to estimate the CO2 emission effects of different ITS services [88]. This methodology is based on an approach to modelling the effects of different types of ITS application at different scales. The project's scope was on surface transport (road, rail, inland waterways and short-sea shipping) in Europe. ECOSTAND [89], a standardized assessment methodology was developed in an international context involving Europe, the USA and Japan. At European level, this has been supported by the ECOSTAND project. Launched in 2010 for a period of three years, the international project ECOSTAND aimed to achieve a standardized framework between the EU, Japan and the USA on a common evaluation methodology to determine the impacts of ITS on energy efficiency and CO_2 emissions. Finally, ICT-EMISSIONS [90] is a methodology based on an innovative easily adaptable and transferrable combination of traffic, driver and emission models. It can quantify energy consumption and CO2 emissions of various ITS categories such as driver assistance systems and eco-solutions traffic management and control measures. Both the theoretical basis and practical examples of applications have been developed with a selection of widely used models.

This is due to the lack of suitable software energy efficiency metrics which are used to estimate the energy requirements of software and hardware. In addition, although certain metrics are available to estimate hardware efficiency, most systems perform multiple operations which make it difficult to separate the energy requirements of ITS and standard day-to-day tasks. Instead, it may be more useful to develop general criteria which reflect the operational performance of the ICT data links using readily available metrics [78] It appears that estimating ICT emissions at the product level is still within its infancy for ITS appraisal, As ITS combines ICT and transport related concepts, it seems advisable to articulate the process around quantitative and non-monetary data values. Overall, the Lifecycle assessment offers a very promising method for estimating emissions throughout the various stages of ITS schemes. The attributional approach is feasible for estimating current ITS scheme emissions using a fixed inventory, while the consequential approach (with a suitable forecasting platform) can be used to estimate the emissions of future technologies in the planning stage or over a longer time frame.

3 Managing Uncertainty in ITS Sustainability Modelling

It is apparent from this critical review of contemporary methods (largely from environmental and socio-economic literature) that uncertainty exists throughout the environmental modelling of transport projects. Although methods have been proposed to deal with this and are discussed later in the paper. ITS however, offers particular uncertainties which current transport appraisal techniques largely ignore, as detailed below.

3.1 Perspectives of Uncertainty

Uncertainty can be defined as a term used in subtly different ways in a number of fields. It applies to predictions of future events, to physical measurements that are already made, or to the unknown. Uncertainty arises in partially observable and/or stochastic environments, as well as due to ignorance and/or indolence. Firstly, the environmental impact is not limited to the road-side but spans multiple locations. Most methods tend to only estimate emissions at a localised area. However, the road infrastructure is served by several ICT data connections, which are controlled by an offsite regional traffic control centre. Without the datacenter, the road-side systems that provide guidance to drivers and enforcement would be inoperable, therefore the emissions and energy of the associated systems should be accounted for. It is therefore important that the system boundary is expanded to cover the system rather than the geographical location, to improve the representation of ITS performance.

The second major uncertainty concerns data collection and is based upon the completeness, accuracy, age, geographical source and availability of data [91]. Using Active Traffic Management (ATM) as an example, the contribution to the environmental impact by the systems within the datacenter that are allocated to the road-side infrastructure must be taken into account. Ideally, this would begin by estimating energy and emissions performance at the software level (the efficiency of the source code within the application that operates the ITS schemes). The next level of allocation is the energy requirements of the hardware (physical electronic equipment) on which the application runs. It should be noted that estimating software energy consumption is high on the research agenda, representing the most recent research in Green ICT [92].

The third form of uncertainty arises from the subjective opinions of multiple stakeholders. Transport is one of the most difficult sectors to decarbonise, arguably due to the variety of stakeholders involved and their conflicting appraisal decisions and targets [93, 94]. This level of conflict must be managed in a formal process that can produce logical conclusions based upon all stakeholder involvement.

3.2 Methods to reduce uncertainty

In estimating the quality of data, methods such as LCA use extensive databases that feature product processes, the most popular being Ecoinvent. This database has its own uncertainty method known as Ecoinvent Lognormal Distribution (ELD). According to Frischknecht et al [95] the ELD assessment takes into account the variability and uncertainty of parameters within the unit process input/output, e.g. measurement uncertainties (the accuracy of the measurement at source), process specific variations (new technologies etc.) and temporal variations (the age of the data when extracted). When using Ecoinvent, an ITS framework could include a Monte Carlo analysis using uncertainty data from the ELD method [96]. Uncertainties could be handled consistently using a Petri matrix originally developed by Weidema and Wesnæs [97]. Uncertainty in the decision making process can be handled by various methods from the field of artificial intelligence that offer decision support capability. Data methods based upon Bayesian subjective probability include Dempster-Shafer theory (DST), which allows evidence to be combined from multiple sources with missing data to give a decision. Kolosz et al [78] combined DST with AHP to estimate the sustainability performance of Active Traffic Management. The main strengths of this approach lie in its ability to treat heterogeneous, uncertain and incomplete data originating from multiple information sources. By combining MCA with fuzzy logic theory [98, 99] new methods have been developed, e.g. Fuzzy AHP [100] and fuzzy comprehensive assessment [101]. Other methods include the field of possibility theory, often considered an extension of fuzzy sets and fuzzy logic.

4 Integrated Sustainability Approaches for ITS

According to Ahlroth et al [31] there is a distinct need for a set of generic weights which can help to harmonise, increase validity and provide cohesion within the various ESAT tools. This is important when joining methods in order to share their output and is an approach which could be adopted to estimate ITS performance. This can be achieved because there is a large degree of overlap between frameworks at different levels. Due to the sheer number of weights and combinations it would prove very complex to map all the possible relationships. A large body of work has focused on developing sustainability indicators to assess changes in transport over a fixed period. According to Gudmundsson

[102] the gap between sustainability indicators and indicator systems currently used is substantial. This argument essentially relates to the lack of metrics to measure sustainability ideals using a system that enforces competent decision making. According to Wallis et al [15], great efforts have happened at the local, national and international levels to select and evaluate various indicators and implement indices to further progress within sustainable development. Over 800 sustainable indicator activities have been listed within the compendium of sustainable development indicator initiatives [103].

4.1 Proposed frameworks

ITS is anticipated to be an important growth area in the next 10–15 years. An estimated $22.4 (€20.4) billion will be invested worldwide on smart transport [104]. Development of structured frameworks for planning, developing, and integrating smart transport technologies (e.g., the National ITS Architecture in the US, the FRAME Architecture in the EU) further reflect the positive intention of transport authorities in developing and deploying smart technologies. These frameworks could identify and assess the potential of individual smart transport technologies, as well as of integration of the technologies.

Work has been ongoing on the smart cities concept, for example sponsored by the European Commission, where ITS has been integrated as part of a strategic IT innovation methodology, commonly known as smart mobility. Lazaroiu and Roscia [105] propose a model for computing "the smart city" indices is proposed. The chosen indicators are not homogeneous, and contain high levels of information. The paper deals with the computation of assigned weights for the considered indicators. Fuzzy logic is used which defines a model that allows "the smart city" to be estimated in order to access European funding. The proposed innovative system results in a more extended comprehension and simple use. Thus, the model could help in policy making process as starting point of discussion between stakeholders, as well as citizens in final decision of adoption measures and best evaluated options. Debnath et al [104] proposed a comprehensive and practical framework to benchmark cities according to the smartness in their transportation systems. The proposed methodology was illustrated using a set of data collected from 26 cities across the world through web search and contacting relevant transport authorities and agencies. Results showed that London, Seattle and Sydney were among the world's top smart transport cities. In particular, Seattle and Paris ranked high in smart private transport services while London and Singapore scored high on public transport services. London also appeared to be the smartest in terms of emergency transport services. The key value of the proposed innovative framework lies in a comparative analysis among cities, facilitating city-to-city learning.

Letaifa [106] argues that despite extensive research on cities' successful transformation into smart cities, a gap exists on how these cities' services shift toward smart services and on the methodology that the cities follow in transforming these services. A qualitative study was designed which builds on an integrative literature review and case studies to propose a methodological framework for the implementation of smart cities.

A Sustainability Assessment Hierarchy (see below) was developed which illustrates the main ESAT models within the Environmental Management field. This maps the most common frameworks with the appropriate methods. The black lines illustrate inheritance and ownership from the strategic frameworks (top) to the approaches (bottom). The red lines indicate the methods that were found to be appropriate for ITS by the authors following the critical review.

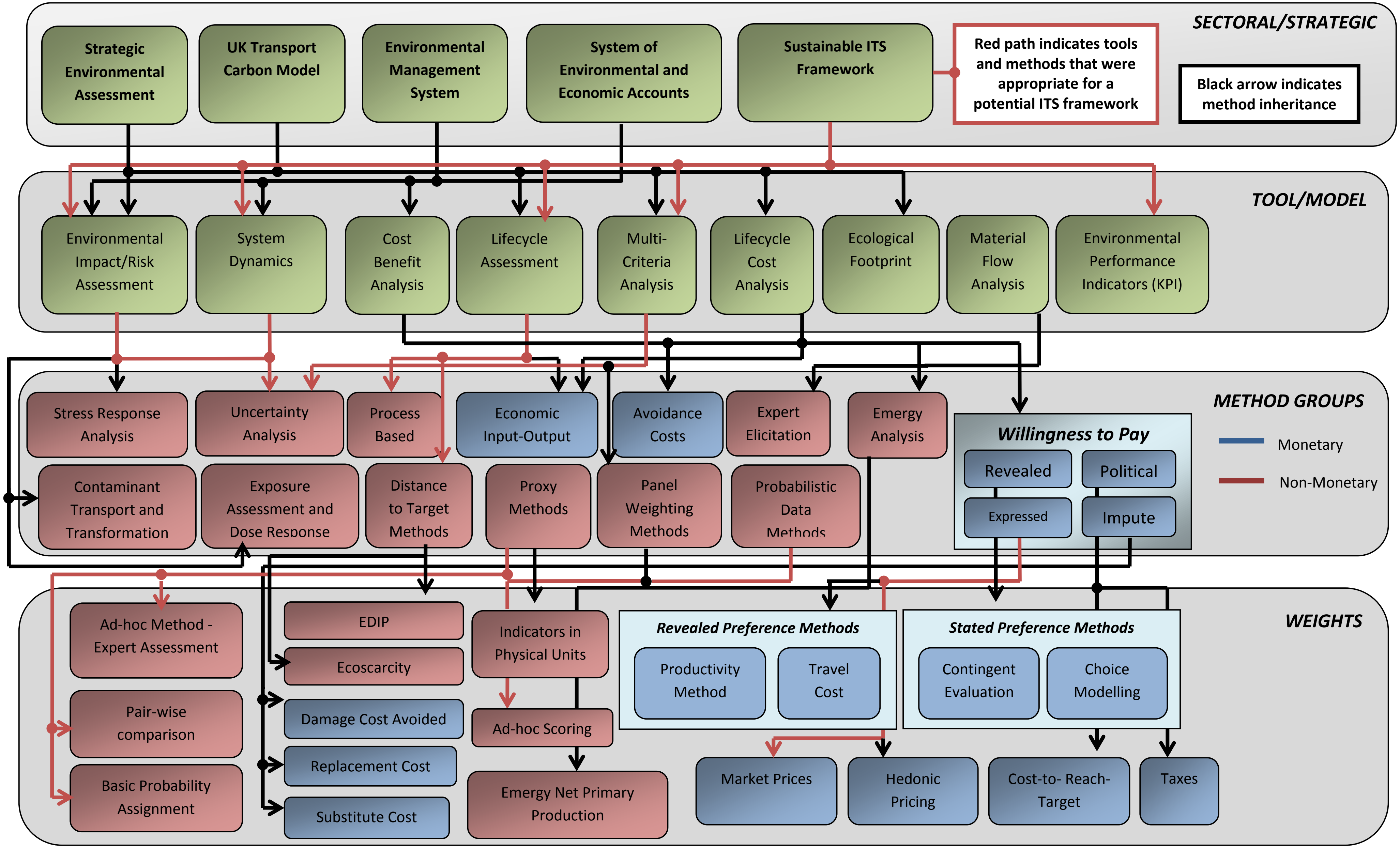

Figure 3: - Sustainability assessment hierarchy (Source: 41)

4.2 Strategic/Sectoral Frameworks

At the strategic level, various frameworks exist which assess environmental management from a top-tier sectoral viewpoint. These frameworks may use a combination of ESAT tools to evaluate the sustainability aspects of large scale generic projects. At this level the frameworks arguably do not share a direct relationship with the weights, rather they select a range of method groups that contain various forms of weighting and valuation. They display the characteristics of each of the strategic frameworks grouped by name, the users, the study object and the weighting of environmental aspects. In addition, the characteristics of values and weights are shown from Monetary, Non-Monetary, Midpoint/Endpoint and finally generic or specific weights that are applied.

Sectoral /Strategic	**Users**	**Study object**	**Weighting of environmental aspects**	**Characteristics of values/weights**		
				Monetary/Non monetary	**Midpoint/ Endpoint**	**Generic or specific weights**
Strategic Environmental Assessment	Policy Makers, Public Sector Agencies	Projects, Policies	Optional	Both	Both	Generic (Primarily)
UK Transport Carbon Model	Policy Makers, Governmental Agencies	Transport Projects and Policy	Optional	Both	Both	Specific
Environmental Management System	Companies, Agencies, Organisation	Management. of Organisation	Required (Significant Impacts)	Non-Monetary (Primarily)	Both	Generic or company specific
System of Environmental and Economic Accounts	Policy Makers, Government Agencies	Policies, Nations, Regions, Sectors	Optional	Monetary	Both	Both
Theoretical ITS Framework	*Policy Makers, Government Agencies*	*Policies, Nations, Regions, Sectors*	*Optional*	*Both*	*Endpoint*	*Both*

Table 2: - Characteristics of Strategic/Sectoral frameworks and values/weights used (Source: Author)

The authors introduced a fictitious ITS framework to be defined at the sectoral level and comprising a number of integrated lower level methods, as highlighted in green. Other related methods include the strategic environmental assessment (SEA) [107, 108], included here to illustrate the sustainability hierarchy. Another tool is the Environmental Management System (EMS). The standardised EMS is a procedural tool which offers structured and effective management of environmental issues in organisations. It includes relational dependencies such as organisational structure, sharing of responsibilities and planning of practices, procedures and resources required to determine and achieve policy objectives [109-111]. Finally, the UK Transport Carbon Model is included as a national strategic level transport model that may reflect elements of ITS in the future [112].

4.2 Tool/Method Level

At the tool or method level, a variety of tools exist which are dedicated to assessing sustainability from contrasting perspectives. These use a significant number of weights and procedures, depending upon the nature and rationale of the methodology. Table 3 presents the various methods, together with local weights and methods within the sustainable management hierarchy. Methods were selected for the theoretical ITS framework on the basis of the highest benefits (from the literature), as highlighted in Table 3. Other available methods included the Ecological Footprint (EF), which in its simplest form represents the rate that humans deplete the earth's natural resources compared to the ecosystems rate of recovery [113, 114]. Originally developed by William Rees and termed 'Appropriate Carrying Capacity', the first EF academic publication was in 1992 [115]. Material flow analysis (MFA) (also referred to as substance flow analysis; SFA) is an analytical method to quantify flows and stocks of materials or substances in a well-defined system. MFA is an important tool to assess the physical consequences of human activities and needs in the field of Industrial Ecology, where it is used on different spatial and temporal scales. Both methods are illustrated here to show variations in weighting and values.

Sectoral Tool/ Model	Users	Study Object	Weighting of aspects	Characteristics of Values/Weights		
				Monetary/Non Monetary	Midpoint/ Endpoint	Generic or Specific Weights
Cost-Benefit/Cost - Effectiveness Analysis	Policy Makers, Public Sector Agencies	Projects, Policies	Required	Monetary	Endpoint preferred/ Both	Generic and site specific
Life-Cycle Assessment	Policy Makers, Public Sector Agencies, Companies	Products, Production Systems, Policies	Optional	Both	Both	Primarily Specific
Life-Cycle Cost Analysis	Companies, Public Sector Agencies	Products, Production Systems	Optional	Monetary	Both	Generic or company specific
Environmental Impact/Environme-ntal Risk Assessment	Policy Makers, Public Sector Agencies, Companies	Projects, Production Systems	Optional	Monetary	Endpoint	Both
Multi-Criteria Analysis	Policy Makers, Governmental Agencies	Policies, Nations, Regions, Sectors	Optional	Both	Both	Both
Material Flow Analysis	Policy Makers, Governmental Agencies	Policies, Nations, Regions, Sectors	Optional	Non-Monetary	Both	Both
Ecological Footprint	Policy Makers, Governmental Agencies	Policies, Nations, Regions, Sectors	Optional	Monetary	Both	Both

Table 3: - Characteristics of Tool/Models and values/weights used (Source: Author)

4.3 Weighting Methods

Each of these methods feature varying sets of weights and whilst largely overlapping, the classifications are based on different rationales [116-119]. Tables 4 and 5 illustrate the characteristics of the weights applied to their parent method within the sustainability field and a brief description of their relevance. (0) indicates the method is completely out of scope, (*) indicates minor elements (such as values of weighting approaches) could be adopted, (**) indicates that major elements can be used and the majority of the weighting approaches can be explored. Finally (***) indicates the method is completely compatible with the study scope. Note that the the weighting methods are a guide rather than a rulebook, and are based upon what the literature suggests as a whole.

The LCA's main impact assessment approach offers the most comprehensive environmental (and to a lesser extent economic) assessment tool which is why it is also selected. In accordance with a suitable emissions database, it can estimate the emissions of ITS services that require physical infrastructure such as the gantries on an ATM scheme. These assessments can include the embodied emissions, i.e. the production of the gantries, the transportation of materials, the energy consumption of the equipment and finally, the installation and disposal emissions. However, for estimating vehicle emissions, it appears preferable to use a more detailed independent approach, estimating traffic flow using the appropriate regional statistics and then using macroscopic traffic modelling to estimate emissions using a specific countries vehicle emission data. A variety of different weighting approaches are available although the most common used is the Eco-indicator 99 weighting approach. This includes the ability to categorise various green-house gasses into Global Warming Potential (GWP).

More recent methods focus upon the midpoint (impact phase). Examples include Ecotax and BEPAS, both methods are based upon monetary valuation of midpoints. According to Finnveden et al [26] recent developments have focused a great deal upon improving the methodology of LCA. For instance, the goal and scope stage can be defined differently when taking into account either attributional or consequential approaches. For the inventory analysis, this is relevant when discussing system boundaries, data collection and allocation. According to Hunt et al [120] and Rebitzer et al [73] it is preferable to simplify data collected from each process (vertical) as opposed to implementing horizontal cut-offs. The latter would involve data compromises in the various (horizontal) phases of a lifecycle such as cradle-to-grave, cradle-to-gate, gate-to-gate and gate-to-grave. It is assumed for the purposes of this research that this type of simplification is not recommended as the weighting and results will differ too substantially from those that would have been produced using a more detailed analysis, particularly when the output is subject to aggregation when combined with other tools such as Multi-criteria analysis, Cost-benefit analysis etc.

Both LCAapproaches (simplified and detailed) also carry some limitations which may affect the accuracy of ITS performance assessment. The simplified variant tends to be insensitive to geographic aspects. For example, the product process which is based upon time and space is aggregated to a point which doesn’t reflect the geographic location of the individual emissions [121]. When assessing an ITS scheme that is particular to a geographical location it is possible that some data for the region may not be available, in which case data from other regions may have to be collected introducing inaccurate final results. The amount of data required to produce a full LCA (compared with a simplified LCA) can be expensive and time consuming, particularly if data on the technology used for ITS is limited or restricted [96, 122]. Finally, it has been observed that both LCA approaches can generate very different results [26, 28, 31, 123, 124]. Impact results typically lack the duration of emissions as well as their concentration. Finally, the functional unit of an LCA consists of a very small assessment space. Various emissions are given a proportional share of the full emissions from each stage. The LCIA must operate on mass loads representing the share of the full emission output from the processes.

Parent method	Weighting approach	Description	Relevance to ITS appraisal
Contaminant Transport and Transformation	Various	Deals with the mitigation of hazardous materials which may cause harm if released on the environment.	0
Distance-to-target Methods	EDIP Ecoscarcity	Enables performance to be estimated based upon the current environmental burden and the minimum value to reach the target. This is very relevant to ITS, however, In order to overcome the limitations of the lack of weighting priorities MCA weighting approaches should be adopted.	**
Economic Input-Output	Various Monetary weights depending on scenario	Assists in measuring the economic lifecycle of a product system. This may prove difficult due to the current lack of economic knowledge of ITS systems.	0
Emergy Analysis	Emergy Met Primary Production	Measures the level of all the direct and indirect energy of the material, services, and information required to make a product or sustain a system. Out of scope.	0
Process based Impact Assessment (LCA)	CML 2001 Eco-Indicator '99 EPS Ecotax BEPAS	LCA's midpoint and endpoint methods are based upon a process based impact assessment. These methods allow the inventory of a product to be categorised into a number of sustainability areas including climate change (mid-point) and damage categories including impact on local health. The CML 2001 method seems suitable due to the focus on climate change, although other methods may be useful.	**
Exposure Assessment and Dose Response	Various	A dose-response relationship describes how the likelihood and severity of adverse health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided). As the scope of the study focuses solely on climate change impact, this	0

		method is out of scope.	
Stress Response Analysis	Various	Stress response analysis can be used to evaluate the potential maximum environmental impacts caused by projects before the system fails. This is out of scope due to the focus on climate change only.	0

Table 4: - Characteristics of tool/models in sustainability field and values/weights used (Source: Author)

Distance-to-target methods like EDIP and Ecoscarcity can be used to evaluate different environmental impact categories depending on the distance between a current level of environmental pollution and a future environmental target value, allowing quantitative weightings to be applied to estimate performance [125-127]. Distance-to-target methods allows performance to be estimated based upon expected targets, whether assessing ITS systems at the regional or international level. While these methods are suitable for ITS, other methods should be used to indicate priority. Targets such as levels of CO_2 need to be incorporated into the performance measurement. Distance-to-target methods provide a promising approach although they need to be expanded in order to take into account not just emissions but also socio-economic criteria, therefore in order to prioritise specific sustainability criteria, a multi-critera analysis method may need to be adopted.

Parent method	Weighting approach	Description	Relevance to ITS appraisal
Expert Elicitation	Various	Expert elicitation is the synthesis of opinions of experts of a subject where there is uncertainty due to insufficient data or when such data is unattainable because of physical constraints or lack of resources. Highly relevant to the study due to potential gaps in knowledge and missing data.	***
Panel Weighting Methods	Pair-wise comparison (AHP, ANP etc) Expert Assessment	Panel weighting methods are based upon Multi-Criteria Decision making. They may contain generic weighting assignments which can be considered very useful to the study.	***
Probabilistic Methods	Basic Probability Assignment	Probabilistic methods such as Dempster-Shafer theory can assign belief to certain categories of performance via basic probability assignment. The method would be very useful in combining evidence from multiple stakeholders in order to assist the proposed framework in making a decision.	***
Proxy Methods	Ad-hoc scoring Indicators in Physical Units	Proxy methods are measurements of physical, chemical, or biological processes that depend on the weather, and therefore provide an indication of past climates. They may be used in order to predict future emissions performance of ITS systems and could be useful in providing initial emission estimates.	**
Uncertainty Analysis	Sensitivity Analysis	Sensitivity analysis can be used to test several scenarios including synthetically altering the opinions of stakeholders in order to test the robustness of the framework.	***
Willingness-to-pay and other socio-economic methods	Cost to Reach target Damage Cost Avoided Hedonic Pricing Market Prices Replacement Cost Method *Revealed Preference* *Stated Preference* Substitute Cost Taxes	Willingness to pay (WTP) is the maximum amount a person would be willing to pay, sacrifice or exchange in order to receive a good or to avoid something undesired, such as pollution. The Cost-to-reach target could be allocated within a distance-to-target method in order to expand its functionality while market prices may be used to forecast expected demand of future ITS technologies.	**

Table 5: - Characteristics of tool/models in transport appraisal and values/weights used (Source: Author)

As there is limited historical data on Intelligent Transport Technologies, Expert elicitation should be used where possible. It is the synthesis of opinions of experts of a subject where there is uncertainty due to insufficient data or when such data is unattainable because of physical constraints or lack of resources [58]. The method is highly relevant to the ITS appraisal in order to cover the potential gaps in knowledge and missing data. Panel weighting methods allow the user to weight particular aspects of ITS sustainability performance, in particular the normalisation of environmental, social and economic criteria. Generalised performance indicators can be developed which can be applied to varying types of ITS technology despite the vast differences in system architecture.

The authors recommend that the probabilistic data fusion method is used for validating ITS performance. Analytical Hierarchy Process could be augmented by the use of Dempster-Shafer theory which is an expanded and formalised version of the original 'theory of evidence' created by Dempster [128]. DST allows certain limitations within the AHP method to be reduced. One criticism of the AHP method is the sheer number of pairwise comparisons to be performed before any rankings can be evaluated [129]. For example, if there were four criteria, each with three decision alternatives there would be 3 comparisons per criterion between the decision alternatives (D.A.'s) level, making 12 comparisons in all at that level. Another 6 comparisons at the criterion level, giving a total of 18 comparison judgements. The number of comparisons quickly rises as the number of alternatives and criteria rise, for example if there were a choice of 8 motorcycles considered then a total of 118 prior comparison judgements would be required. DST reduces this limitation through by allowing groups of DA to be compared, effectively minimising pairwise comparisons. A further drawback is their consistency of these comparisons. For example, if car A is preferred to B, B preferred to C also C preferred to A, this would be understandably inconsistent. This understanding of consistency is measured and discussed within the AHP method. Additionally there is no allowance for ignorance with respect to types of car and available criteria while DST supports it.

The original 'theory of evidence', created by Dempster [128] was based around Bayesian probability inference (BPI) in that it deals with subjective beliefs and can handle qualitative as well as quantitative data values. Proxy methods also provide useful measurements of physical, chemical, or biological processes that depend on the weather, and therefore provide an indication of past climates. They may be used in order to predict future emissions performance of ITS systems such as Intelligent Speed Adapation and the Automated Highway System and could be useful in providing initial emission estimates.

5 Discussion and Conclusions

A critical review of various ESAT tools has been carried out to identify suitable approaches for estimating the sustainability performance of ITS. From the review, it is clear that each individual method features different types of approaches that can be used to assess differing aspects of ITS based upon duration, scope and technology. In terms of duration, Environmental Impact assessment is useful for assessing ITS performance in the short term using before and after analysis, but due to ITS systems possessing a marginal relationship with the land, this method may not be suitable. The cost benefit analysis and cost effectiveness analysis also perform well when assessing short-term impacts with limited focus but may become inaccurate when attempting to estimate environmental costs when attempting to take into account environmental impacts over a long time period (typically over 15 years). Dual discounting within CBA seems to provide a reasonable solution to this issue. Lifecycle assessment features a more rigorous approach in the form of past (embedded), present (operational) and future (disposal) estimations using environmental data sets such as the Ecoinvent database. It is also the most thorough with the disadvantage being that not all the data may be up-to-date or available at all. Overall impacts can therefore be assessed using a Multi-criteria analysis approach such as the analytical hierarchy process, however, care must be taken when selecting the appropriate performance indicators as well as a high risk of selection bias if the priority is on a specific type of criterion such as safety.

The main issue when assessing ITS benefits mainly rests upon the vastly differing configurations of ITS systems, some or all of the methods mentioned may encounter issues when used independently, and a combination of methods such as the integrated approach described in this paper may need to be used. When comparing different technologies, a normalised uncertainty method should be adopted. The methods highlighted in this review refer to performance improvements as a mathematical theory of evidence where different stakeholders can prioritise their own specific performance areas. From the review, it is evident that the individual methods cannot act alone in the appraisal of ITS. Instead, a combination of approaches should be used to assess different perspectives of sustainability. For example, CBA in its current form may be used to assess monetary values but is unsuitable for the appraisal of the environment and climate change. Carefully balancing each ESAT tool with its appropriate weights and methods is crucial to harmonise the assessment process of ITS. Uncertainty needs to be managed by an appropriate method as ITS systems span multiple locations (i.e., the road-side and datacenter of the traffic control centre). Whilst the selection of methods adopted here have been tested in Kolosz et al [78] and Kolosz [41], they are just one feasible combination. It is therefore important to note that the goal of the review was to highlight ongoing research in ITS appraisal, to stimulate debate in the authors selection of methods and to support the development of an official ITS framework as the technologies become more commonplace.

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