Published article:

Kolosz, B, Grant-Muller, S and Djemame, K (2013) *Modelling uncertainty in the sustainability of Intelligent Transport Systems for highways using probabilistic data fusion.* Environmental Modelling and Software, 49. 78 - 97. ISSN 1364-8152

http://dx.doi.org/10.1016/j.envsoft.2013.07.011

Koloz B, Grant-Muller S M and Djemame K (2013) 'Modeling uncertainty in the sustainability of intelligent transport systems for highways using probabilistic data fusion'. Environmental Modelling & Software 49 (2013) 78-97 DOI: 10.1016/j.envsoft.2013.07.011 (pre-publication version)

'MODELLING UNCERTAINTY IN THE SUSTAINABILITY OF INTELLIGENT TRANSPORT SYSTEMS FOR HIGHWAYS USING PROBABILISTC DATA FUSION'

Ben Kolosz, Institute for Transport Studies, University of Leeds
E-mail: tsbwk@leeds.ac.uk
Tel: 0113 34 31798
Institute for Transport Studies, University of Leeds, 36-40 University Road, Leeds LS2 9JT

Dr Susan Grant-Muller, Institute for Transport Studies, University of Leeds
E-mail: S.M.Grant-Muller@its.leeds.ac.uk
Tel: 0113 343 6618
Institute for Transport Studies, University of Leeds, 36-40 University Road, Leeds LS2 9JT

Dr Karim Djemame, School of Computing, University of Leeds
E-mail: scskd@leeds.ac.uk
Tel: 0113 3436590
School of Computing, University of Leeds, Leeds, LS2 9JT

'MODELLING UNCERTAINTY IN THE SUSTAINABILITY OF INTELLIGENT TRANSPORT SYSTEMS FOR HIGHWAYS USING PROBABILISTC DATA FUSION'

Abstract

The implementation of ITS to increase the efficiency of saturated highways has become increasingly prevalent. It is a high level objective for many international governments and operators that highways should be managed in a way that is both sustainable i.e. environmental, social and economically sound and supportive of a Low-Carbon-Energy Future. Some clarity is therefore needed to understand how Intelligent Transport Systems perform within the constraints of that objective. The paper describes the development of performance criteria that reflect the contributions of Information Communication Technology (ICT) emissions, vehicle emissions and the embedded carbon within the physical transport infrastructure that typically comprises one type of Intelligent Transport System i.e. Active Traffic Management – a scheme that is used to reduce inter-urban congestion. The performance criteria form part of a new framework methodology ‘EnvFUSION’ (Environmental Fusion for ITS) outlined here. This is illustrated using a case study where environmental performance and pollution baselines (collected from independent experts, academic, governmental sources and suppliers) are processed using an attributional Lifecycle Assessment tool. The tool assesses the production and operational processes of the physical infrastructure of Active Traffic Management using inputs from the 'Ecoinvent' database. The ICT component (responsible for data links) is assessed using direct observation, whilst vehicle emissions are estimated using data from a National Atmospheric Emissions Laboratory. Analytical Hierarchy Process and Dempster-Shafer theory are used to create a prioritised performance hierarchy: the Intelligent Transport Sustainability Index, which includes weighted criteria based on stakeholder expertise. A synthesis of the individual criteria is then used to reflect the overall performance of the Active Traffic Management scheme in terms of sustainability (low-carbon-energy and socio-economic) objectives.

Keywords: - Uncertainty Modelling, Low carbon-energy policy, Intelligent

Transport Systems,

1 Introduction

1.1 Problem rationale

The potential global warming crisis has called for technology within the transport sector which is able to produce efficiency benefits for the transport system, but which operates in such a way that it is not detrimental to the local and global environment. 'Intelligent Transport System' (ITS) is a broad term used to describe systems based on a combination of Information Communication Technology, positioning and automation technologies (Psaraki et al, 2012). In terms of road transport, their aim is to maximise the operational capacity of highways, offering enhanced performance within the transport network so that the need to construct additional road capacity can be avoided (Deakin et al, 2009; Žilina, 2009). These technologies can also serve to reduce emissions, maintain or increase safety, generate societal benefits (such as accessibility), maintain compliance and reduce economic expenditure. However, little is known about the actual contributions of intelligent transport systems in highways to climate change mitigation of private vehicle transport.

The concept of sustainability has been widely applied and usually attempts to integrate environmental social and economic concerns although there is still ambiguity in its terms of reference (Hilty et al, 2006; Matthews et al, 2007). In this research a method to assess the performance (in terms of sustainability) of an ITS scheme is developed, where sustainability is used to reflect environmental, economic and social (safety and scheme compliance) terms. A range of both quantitative and qualitative indicators used to reflect these three aspects, as defined in subsequent sections of the paper. In order to assess the sustainability of ITS, the emissions from ICT and infrastructure for their whole lifecycle need to be considered alongside the potential gains through increased traffic flow efficiency. ICT works as an enabler within ITS systems in order to improve the performance of the road network by improved control and supervision. According to Patey et al (2008) no studies at that time had focused on the embedded lifecycle emissions in the construction, operation and disposal of ITS schemes. In addition, there is no 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 technology.

The environmental impacts of ITS also sit alongside the carbon offset that these technologies generate by improved management of the transport network (i.e. through smoother flowing traffic, reduced congestion overall). Using current methods, the ICT support infrastructure, physical transport infrastructure and the operational assessment of vehicle throughput have all been calculated in isolation. Without a calculation of the overall emissions generated there is the risk that some elements remain unaccounted for, for example 'cause and effect' chains and hidden consequences. The aim of the research here is to extend the scope of the emissions accounted for to include both the potential carbon reduction from operating an ITS scheme and the embedded emissions from constructing and implementing the scheme.

The paper therefore introduces a 'unified' environmental and socio-economic framework, covering both current ICT standards and transport impact assessment. It is also able to take inputs from various deficient or uncertain data sources in order to quantify overall performance against sustainability criteria. The method is illustrated using a case study assessment of one particular type of ITS: the UK Highways

Agency’s active traffic management (ATM) scheme as implemented in the Birmingham area on a 16.4 km inter-city stretch of highway.

Measures which were implemented are temporary shoulder use, lane enforcement and queue warning systems. Furthermore the framework has been developed in a flexible way so that it may be applied with all forms of inter-urban ITS schemes internationally.

1.2 The introduction of Active Traffic Management

Active Traffic Management (ATM) is an international 'smarter highways' concept consisting of a collection of various systems working to reduce road congestion and improving traffic flow. It includes a feedback process of traffic data to the central highway control centre, which (following data analysis), allows human operators to implement dynamic changes to the highway signs and controls in response to current conditions. ATM also supports operations planning, which includes evaluating the expected road network performance under various future scenarios, such as increases in demand, lane closures, special events, etc. It is then possible to develop control strategies that may improve performance and test these strategies in terms of their cost and the benefits they bring under these future scenarios. Finally, the decision support system can be run in real time, which includes filtering the measurement data, providing short term prediction of the traffic state, and selecting the best available control strategy for the next one or two hours.

ATM has been introduced in many countries worldwide for several reasons, but its primary role is to reduce traffic congestion. For example, in the UK by 2005 the road network operator's highway building allowance was £3 billion over budget, causing the Department for Transport to consider alternatives to further conventional highway widening schemes. In 2006, the successful trial near

Birmingham (UK) of the M42 ATM on the 16.4 kilometre stretch of road between junction 3a to 7 took place.

By 2008 this type of scheme became a necessity as road traffic in Great Britain had grown by 84 per cent since 1980, from 172 to 318 billion vehicle miles (Department for Transport, 2008). The majority of the growth was in car traffic which had risen by 87 per cent since 1980, from 134 to 250 billion vehicle miles.

In the USA, the Washington State Department of Transportation implemented their first enforceable ATM schemes in 2010 in the Seattle Metropolitan area with heavy fines if road users did not comply with the stated speed limits (WSDoT, 2012). ATM systems were activated on 11.6 km (7.2 miles) of the I-5 northbound carriageway in August 2010 and were expanded in 2011. The primary ATM strategies were ramp metering, queue protection, temporary shoulder running, junction control, and lane-specific signalling.

In Germany, the Federal Highway Research Institute reported demand on the network had increased and is expected to increase an additional 16 percent for passenger transport and 58 percent for freight transport by 2015 (Bolte, 2006). Their traffic management strategies include speed harmonisation, queue warning, temporary shoulder use, junction control, truck restrictions, ramp metering, dynamic rerouting, traveller information and truck distance tolling (Mirshahi et al, 2007).

The Netherlands have implemented similar systems, including the addition of a tidal flow scheme. The only tidal flow lane in the Netherlands was originally opened as a car-pool lane in 1992. This lane operates in the morning peak inbound direction toward Amsterdam and outbound in the evening. It is noteworthy that ATM is preferred by international transport decision makers to road widening due to the reduced costs compared with widening highways and the decreasing availability of land for use in widening schemes.

For example, the M42 scheme in the UK cost £96.4 million compared with the £500 million that it would have cost to widen a section of highway. It is estimated that it takes on average 10 years to implement a widening scheme as opposed to 2 years for ATM with variances in road type, region and country. The following sections of this paper introduce the EnvFUSION methodology and illustrate the process to estimate the environmental and socio-economic impact using the case study of ATM on the M42 stretch of road.

2 EnvFUSION methodology and related literature

EnvFUSION has been designed as an internationally relevant, integrated assessment approach as part of a wider strategic performance management framework (Kolosz et al, 2012). The framework consists of a Lifecycle inventory (LCI) and Lifecycle Impact Assessment (LCIA) (taking an attributional assessment approach), together with priority setting and pair wise comparison using an Analytical Hierarchy Process (AHP). Dempster-Shafer theory (DST) is used in combination with AHP to form an intelligent transport sustainability index using subjective quantitative probability assignment. The rationale for integrating AHP and DST is that conventional DST does not differentiate the importance of different types of evidence (Ju and Wang, 2012). In reality, the decisions to proceed with many transport projects are founded on some subjectivities, including the prioritisation by decision makers of various targets which aim to reflect socio-economic and environmental objectives. There are therefore advantages deriving the method so that it can reflect both objective quantitative and subjective qualitative data.

Figure 1 illustrates the EnvFUSION method overall and is followed by an overview of the different elements. The role and rationale for use of the particular elements is presented together with some discussion of potential weaknesses.

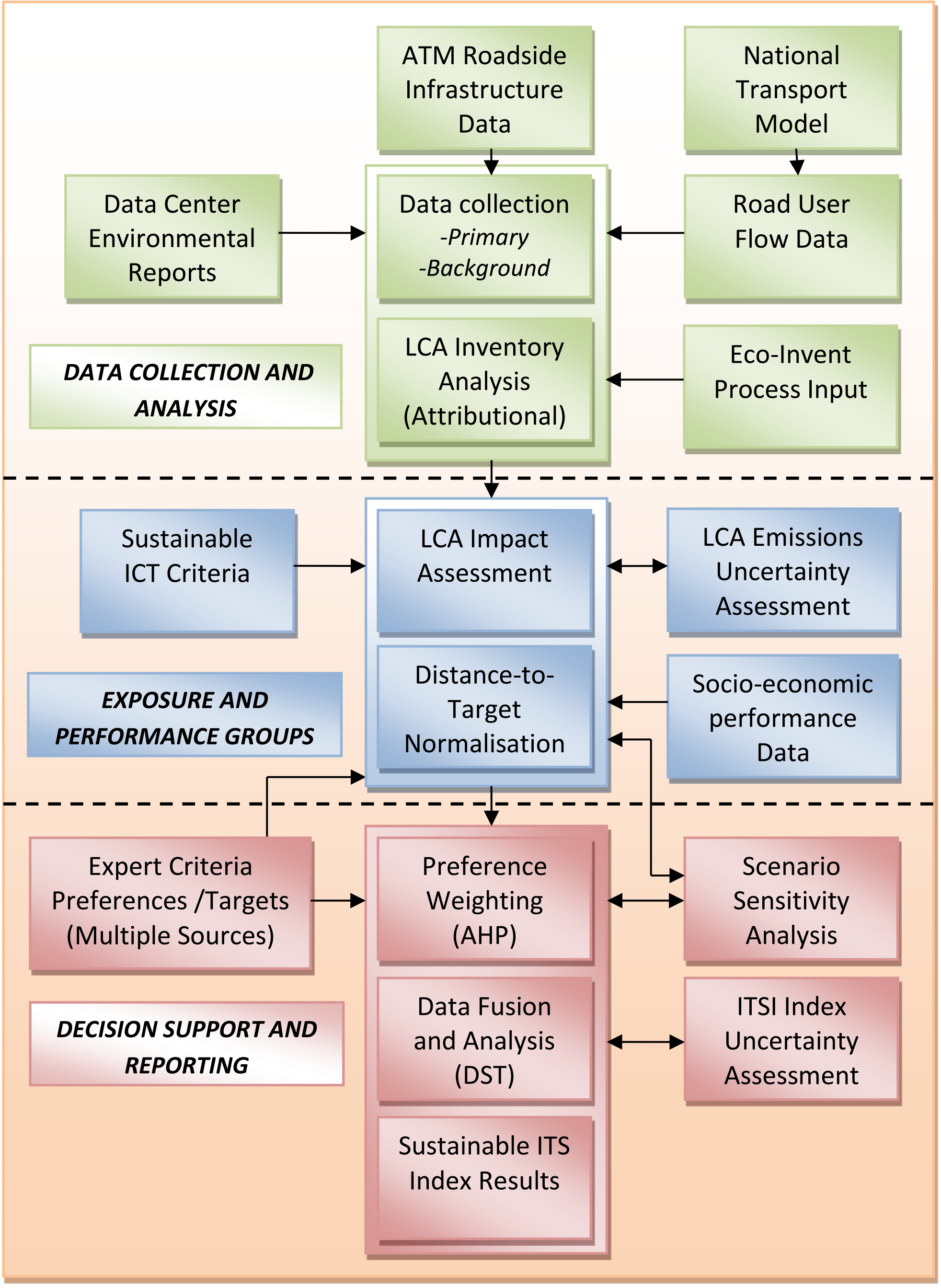

Figure 1: Overview of EnvFUSION methodology

2.1 Lifecycle Assessment for Intelligent Transport

2.1.1 Description

Lifecycle Assessment (LCA) can be described as an Environmental Systems Analysis tool (Ahlroth et al, 2011) and has been incorporated within the EnvFUSION framework due to its detailed emissions modelling capability (Rebitzer et al, 2004). It was first established in the 1990's, slowly gathering international recognition and popularity as the first research publications emerged (Guinée et al, 1993a; Guinée et al, 1993b; Finnveden et al, 2009). It was later subject to some criticism by the academic community due to the resource intensive data collection and computation needed. LCA techniques have since advanced considerably, assisted by the introduction of an international standard (ISO 14040) intended to harmonise the methodology across different regions and countries (International Standards Organisation, 2006; Arvanitoyannis, 2008) and improve access to the background data through the Swiss Ecoinvent database (Frischknecht and Rebitzer, 2005). Guidelines have also been developed which include process optimisation, (Pieragostini et al, 2012) parameterisation of inventory data (Cooper et al, 2012) and techniques to improve LCA as an approach for environmental analysis (European Commission JRC, 2010a, b).

The literature highlights many different LCA approaches, although two are dominant i.e. attributional LCA and consequential LCA (Rebitzer et al, 2004; Finnveden et al, 2009; Mathiesen et al, 2009). The attributional approach is essentially a point estimate in time and usually 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 (Sandén and Karlström, 2007;

Brander et al, 2009; Chen et al, 2012). The most appropriate choice of approach largely depends on the product or service under assessment.

Finally, there is the option to perform either a simplified or full LCA, with the former being affordable and quick to calculate and the latter being more accurate at the cost of intensive data collection. According to Hunt et al (1998) and Rebitzer et al (2004) 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. 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 of the LCA is subject to aggregation using a normalisation method such as AHP.

2.1.2 Limitations of LCA

Whilst being a popular and effective assessment tool, each type of LCA also carries some limitations. Simplified LCA's tend 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 (Ossés de Eicker et al, 2010). When assessing a 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 is limited or restricted (Christiansen and SETAC-Europe, 1997; Goedkoop et al, 2010).

Finally, it has been observed that each of the different LCA approaches available can generate very different results (Finnveden et al, 2009; Higgs et al, 2010; Ahlroth et al, 2011; Cherubini and Strømman, 2011; Malça and Freire, 2011).

2.1.3 LCA studies applied to Intelligent Transport Systems

To the best of the authors' knowledge to date no LCA studies for inter-urban ITS schemes have been published. However, numerous LCA studies have been carried out within the transport sector focusing, for example, on traffic throughput (Spielmann and Scholz, 2005; Leduc et al, 2010), Input-Output models for economic supply and demand, alternative fuels (Finnegan et al, 2004) and vehicle technologies (Rajagopal et al, 2011). In terms of scope, the Ecoinvent database also includes various logistics inventory data for freight transport including heavy goods and passenger vehicles (Spielmann and Scholz, 2005). In relation to road transport and ITS, ICT systems may include roadside infrastructure for displaying messages, data centers for storing traffic information, traffic control systems and general telecommunication services such as surveillance and route guidance. It is therefore worth noting that LCA studies on ICT production have also been undertaken.

According to Higgs et al (2010) a great deal of effort has recently been made to define the whole lifecycle of energy production and CO_2 impact of ICT, in addition to the materials used in the manufacturing process. This research is still in its early stages however, as calculation of the levels of energy and CO_2 within the ICT supply chain is complex due to the almost infinitesimal configurations of equipment (Stobbe et al, 2009; Dao et al, 2011). Estimating ICT emissions at the product level is out of scope for this paper (see future work). Instead, general criteria are given which reflect the operational performance of the ICT data links using metrics that are readily available.

2.2 Multi-criteria Decision Making with AHP/DST

The decision making method for the EnvFUSION framework uses a combination of two techniques: Analytical Hierarchy Process is used to prioritise and weight various performance criteria into groups of decision alternatives whilst Dempster-Shafer theory combines all available data sources using criteria from the Analytical Hierarchy Process using a quantitative fusion process. This allows uncertainty to be quantified, which may arise from the LCA and other inputs such as data from ITS experts and published literature sources.

After data fusion, the Dempster-Shafer process takes the Analytical Hierarchy Process weights for each criterion as a multiplier and sums the probabilities of each criterion (with their weights) to produce an overall performance value for the ATM scheme. The configuration of sustainable performance using Dempster-Shafer theory in this paper has been influenced by Awasthi and Chauhan (2011). The methods are described in more detail below.

2.2.1 Analytical Hierarchy Process

Analytical Hierarchy Process has been included in the EnvFUSION framework due to its ability to support calculation of criteria scores and its transitivity properties (Awasthi and Chauhan, 2011). However, its main advantage here is its ability to facilitate prioritisation by decision makers of the three main pillars of sustainability, i.e. the social, economic and environmental facets. It is a technique pioneered by Thomas Saaty (1980) in order to organise and analyse complex decisions. According to Brucker et al (2004) Analytical Hierarchy Process is one of the most widely used methods within the multi-criteria decision method group.

It enables the user to establish weights for selected impact criteria through the use of pair-wise comparisons and is based upon three elements[i]: the construction of a hierarchy, priority setting and logical consistency (Saaty, 1990; Hermann et al, 2007; Sambasivan and Fei, 2008). According to Brucker et al (2004) and Saaty (1990) criteria within MCA can be generated spontaneously.

2.2.2 Dempster-Shafer theory with AHP

In EnvFUSION, Analytical Hierarchy Process is augmented by the use of Dempster-Shafer theory which is an expanded and formalised version of the original 'theory of evidence' created by Dempster (1968). It allows users to combine evidence from different sources and arrive at a degree of belief (represented by a belief function) that takes into account all the available evidence. DST is a probabilistic method, used in a variety of applications including expert systems, information fusion, risk analysis and artificial intelligence (Shafer, 1976; Awasthi and Chauhan, 2011). It was chosen over other decision support methods supporting uncertainty such as Association Rules, Fuzzy Logic (possibility theory) and Probabilistic Neural Networks as they lack the ability to unify groups of solitary data, whilst DST's main strength is in allowing evidence to be derived from multiple sources, both objective and subjective. Transport decision making also tends to produce differences between various stakeholders which DST is able to quantify. Whilst AHP serves the function of making priorities between criteria explicit, DST enables a unified decision to be made by fusing the opinions of multiple stakeholders to a single measure of performance for each criterion. DST and AHP therefore act in synergy in the

EnvFUSION framework The first integration of these two techniques (AHP and DST) was undertaken by Beynon et al (2000).

Some of the main benefits of DST include the ability to handle uncertainty, missing or incomplete data, as well as data fusion and the aggregation of different data types (Shafer, 1976; Dempster, 2008; Awasthi and Chauhan, 2011; Yao et al, 2012). This is particularly relevant in this context as some data may be unavailable through the primary data collection phases of the framework (Lifecycle material inventory) and DST can compensate for this using probabilistic data values. DST can reduce uncertainty (both objective and subjective) as well as maintaining the harmonisation of qualitative and quantitative data between the transport and ICT performance criteria.

2.2.3 Limitations of the DS/AHP methods

Some limitations exist in each of the methods and it is worth addressing these before further elaboration of the framework. For AHP, the number of pair-wise comparisons that may be needed by the experts can be onerous. This is an issue of both fatigue and time resource but can be overcome by considering groups of decision alternatives. In some circumstances, DST may also be paradoxical in that the results may be counter-intuitive when confusing probabilities of truth with probabilities of provability. This is avoided in this method due to the development of a pragmatic underlying rule-set which provides meaning to the probability values.

A further drawback arises in the consistency of the comparisons when a large number is needed, but this may be addressed by careful design of data collection.

2.2.4 Applications of DST/AHP in transport

The literature illustrates a limited number of studies that combine AHP with DST within the transport field, however to the best of the authors' knowledge no studies have been published specifically related to Intelligent Transport Systems.

One study example from the wider transport field is Awasthi and Chauhan (2011) who integrated AHP and DST to calculate the emissions and socio-economic impact of car-sharing within an urban environment. While they successfully deployed DST to compensate for incomplete or missing data, the benefit of using the technique over other multi-criteria decision making tools isn't elaborated.

2.3 Combining LCA and DST/AHP

To date it has not been possible to find published academic literature that combines Lifecycle Assessment with AHP and DST and therefore such an approach is novel. However, Hermann et al (2007) have combined Environmental Performance Indicators, LCA and AHP. Their approach involved a linear aggregation of the environmental performance indicators, using a cradle-to-grave LCA to assess emissions that were based upon organisational criteria established through AHP. The disadvantage of this approach was that the LCA involved much simplification, resulting in a loss of some of the necessary accuracy for full emissions calculation. The approach adopted here mitigates this by using a simplified LCA as only one of three data sources within the model. When the emissions data has been processed using an impact assessment method, the model then combines the ICT and transport network throughput data with the LCA outputs into the ITS sustainability index using DST and AHP. Some recent literature has been concerned with the integration of uncertainty evaluation in LCA by including fuzzy multi-criteria analysis as well as other decision making methods (see for example Basson and Petrie (2007) and Benetto (2008)). In section 3 below, a description of the framework is given, demonstrating how the three methods (LCA/DST/AHP) inter-relate within the EnvFUSION framework overall.

3 Framework Development and Integration

This section discusses the development of the framework, beginning with a description of the criteria selection process that together reflect the sustainability objective. This is followed by an outline of the LCA emissions modelling process and definition of the ICT operational efficiency criteria. The information fusion process is then described and finally, the overall ITS sustainability index is given.

3.1 Criteria Selection and Weight allocation

The intial step in the framework is the selection of criteria for the environmental assessment of the ATM scheme. In practice this resulted from a process of literature study, expert brainstorming and peer review with the outcome as shown in Figure 2. Experts within the academic community and the road network operator then rated and prioritised the criteria using the AHP method as follows. The problem was firstly defined by structuring the hierarchy from the bottom (alternatives) through the intermediate levels (criteria) to the top (objectives). A set of pair-wise comparison matrices were then constructed for each of the lower levels with one matrix for each element in the level immediately above using the pair-wise Likert scale (Table 1).

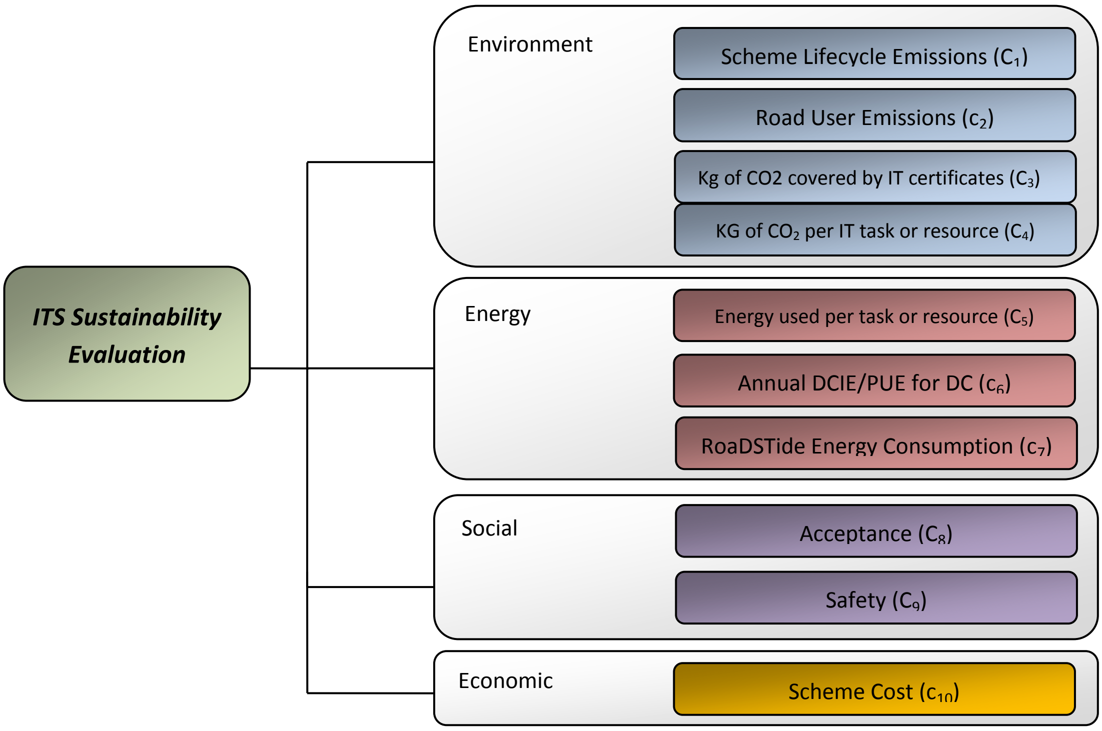

Figure 2: - Evaluation Criteria within the EnvFUSION framework

Numerical Rating	Opinion/Knowledgeable
1	No Opinion/Equal
2	Favourable
3	Moderately Favourable
4	Strong
5	Extremely favourable (Max)

Table 1: Pair-wise Comparison Likert scale used within EnvFUSION

For more information on the AHP methodological process, see for example Saaty (1980) and Beynon (2002).

3.2 LCA Emissions Modelling in EnvFUSION

The Simapro software package (developed by PRe Consultants in Holland) provided a platform for modelling all phases of the LCA for the ITS infrastructure, including the inventory analysis and impact assessment (Goedkoop et al, 2010). The Ecoinvent database was used to assign the materials that were collected from the suppliers into their appropriate LCA upstream unit processes (Frischknecht et al, 2005). A significant amount of uncertainty exists during this phase, as the background process consists of data based on average European demand patterns.

For the inventory analysis, Ecoinvent features its own uncertainty assessment: Ecoinvent Lognormal Distribution (ELD). According to Frischknecht et al (2005) the ELD assessment takes into account the variability and uncertainty of parameters within the unit process input/output such as 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). The EnvFUSION framework undertakes a Monte Carlo analysis using uncertainty data from the ELD method (Goedkoop et al, 2010). Uncertainties are handled consistently using a Petri matrix originally developed by Weidema and Wesnæs (1996).

The square of the geometric standard deviation for use in the calculation of the confidence interval (95% interval - SD_{g95}) or (σ_g^2) is then calculated using equation (1)

$$SD_{G95}^2 = \sigma_g^2 = exp^{\sqrt{[\ln[(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \qquad (1)$$

Section 5.2.4 provides an illustration of the uncertainty calculations for the case study used in this research. A number of impact assessment (mid-point) methods are potentially available, however the CML 2001 (Centre of Environmental Science of Leiden University) model was selected for use in EnvFUSION. This was to allow the characterisation of the normalised emissions at the mid-point level rather than the damage assessment level, which is out of scope for the framework. The global warming potential model was extracted from the IPCC's (Intergovernmental Panel Committee on Climate Change) own accounting methodology, which gives the carbon equivalent per kilo of greenhouse-gas emission over a period of 100 years. The geographic scope for this method is set at the global scale (IPCC, 2001; Goedkoop et al, 2010).

3.3 ICT operational efficiency criteria in EnvFUSION

In order to calculate the operational emissions of the ICT data links, various energy efficiency metrics and indicators were adopted from the literature leading to the criteria summarised in Table 2.

Parameters/Criteria	***Display Format***
Energy used for task or resource	KWh
CO2 per task or resource	KG CO2 eqv
Kg of CO2 offset	KG CO2 eqv
Kg of CO2 covered by renewable energy certificates	KG CO2 eqv
What is your annualized average PUE/DCIE? (last 12 months)	<Range 1 – 2.5> or <%>
Are you European Code of Conduct for Datacenter compliant?	Yes/No (Endorser or full participant)
Do you have an Energy Star for Datacenter rating	<Points range or star rating, no,>
Are you LEED (or BREEAM) for data center rated?	<Platinum, gold, silver, bronze, no etc>

Table 2: ICT Infrastructure Criteria

Since the case study used in this research (the M42 ATM project) also required the reconfiguration and enhancement of communication systems at the west midlands regional control centre, it was important to quantify the energy and emissions consumption of this change where possible. Energy used per task (or resource) indicates the shared resources towards managing the ITS technology on the roads and is measured in kW/h. CO_2 per task (or resource) focuses on the carbon emissions, whilst the KG of CO_2 carbon offset indicates the saving of CO_2 for the ITS schemes that are linked to the data center. This is disaggregated further into a criterion that determines whether the offset stems from renewable certificates. Power Usage Effectiveness is defined as the total efficiency of the data center (2).

Note that at the time of writing, the average data center (internationally) has a Power Usage Effectiveness of 1.8-1.89 from a recent survey conducted by the Uptime Institute (Stansberry and Kudritzki, 2012) .

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \quad (2)$$

Data center infrastructure efficiency is the measure preferred by data center operators, defined by the inverse calculation of (2) expressed as a percentage. Other certificates include Certified Energy Efficiency Data Center Award developed by the British Computing Society giving a subjective score of gold, silver and bronze depending on the efficiency (Chartered Institute for IT, 2011). It was developed using the EU code of conduct for data center energy efficiencies best practice guidelines, which consists of minor or major improvements which will contribute to energy efficiency. A subjective rating of YES or NO is given. The Energy Star for data centers is a joint program between the U.S. Environmental Protection Agency and the U.S. Department of Energy and assesses the efficiency of individual hardware, most recently buildings (i.e. data centers). The award is given with both a points system and a certification for meeting minimum standards. The final criterion reflects achievement against Leadership in Energy and Environmental Design or Building Research Establishments Environmental Assessment Method.

3.4 EnvFUSION Information Fusion and Indicator Estimation

The data (basic probability assignments and mass functions) are required for each of the criteria (Figure 2), which in practice may be generated from a number of sources including experts, IT environmental reports, the LCA model within EnvFUSION and direct measurements. It should be noted that sources that use their own grading system will be able to subjectively rate performance using this method.

Table 3 illustrates a performance ranking in order to assign belief vectors to the basic probability values from various sources with uncertain data.

Grade	***Performance Ranking***
No Target (NT)	0.1
Very Low (VL)	0.3
Low (L)	0.5
Medium (M)	0.7
High (H)	0.9
Very High (VH)	1.0

Table 3: Performance Sustainability Scale

Peer experts provide the Basic Probability Assignments (BPA) either directly or from a pair-wise questionnaire. These different sources are then aggregated using DST. A distance-to-target (DTT) method (Weiss et al, 2007) is used to normalise the probability values based upon expected future targets that are set by the road network operator. These targets can also be aligned by local, regional and international government bodies and institutions. Whilst DTT was originally derived as a LCA method to evaluate and prioritise the different environmental impact categories, in this research DTT has been expanded to incorporate environmental issues (such as emission levels, energy consumption), social perspectives (such as road user acceptance), safety and finally, scheme cost. The method is modified to give an aggregated score while AHP enables prioritisation. The reduction targets can be achieved by marginal improvements in technology. This allows the LCA method to be in full synergy with AHP and DST as opposed to acting as just an input value to the information fusion process. Using a version of the DTT method proposed by Weiss (2007), the difference between the apparent status of a criterion per year and a future target value is calculated as:

$$DTT_{(i)} = ASB_{(i)} - FST_{(i)} \tag{3}$$

With $DTT_{(i)}$ being the distance-to-target value dependent on the context of the particular criteria, $ASB_{(i)}$ the apparent level of environmental, social and economic burden represents the definition of sustainability in the model and $FST_{(i)}$ the future 'sustainability target'. In this context, sustainability takes a value which considers all facets of evidence in the form of a sustainability index (representing the prioritised set of criteria). In order to determine the performance ranking $PR_{(i)}$ of a specific criterion, the future sustainability target (comprising the environmental and socio-economic criteria below) is divided by the performance burden related to the specific criterion, which gives a value representing a distance to target weight.

$$PR_{(i)} = \frac{FST_{(i)}}{ASB_{(i)}} \tag{4}$$

The distance to target weights for the particular case study used in this research are provided in the case study results within Section 5.

Using this proposed solution for calculating uncertainty within the context of the M42 ATM scheme, the following calculations were based upon Awasthi and Chauhan's (2011) approach to assigning belief. Using the individual performance rankings in Table 3 we have $G_k \in \{NT, VL, L, M, H, VH$ and the BPA for each information source, the overall performance weights (*r_i*) for a criterion *i* would then be calculated as follows:

$$r_i = \sum_{k=1}^{p} r\,(G_k)\ \times bpa\,(G_k)\ \times DTT_i \tag{5}$$

Where (G_k) represents the global performance ranking $G_k \in \{NT, VL, L, M, H, VH\}$ represents the individual performance ranking of a sustainability grade G_k, bpa (G_k) represents the basic probability assignment or mass function related to each sustainability grade G_k and P represent the number of grades applicable. $P = 6$ for $G_k \in \{NT, VL, L, M, H, VH\}$. DTT_i is the distance to target weight for a criterion *i* which is calculated after the bpa's have been converted by the overall performance ranking.

3.5 The EnvFUSION ITS Sustainability Index

Overall performance rankings are used to assess the level of emissions and socio-economic aspects of the ITS scheme using an intelligent transport sustainability index. The overall performance rankings for the criteria $C_1, C_2,..., C_N$ are denoted by r_1, r_2, r_3,... r_N. An ITS sustainability index value is then given by combining:

$$ITSI = \mathrm{r}_1 \times w_1 + \mathrm{r}_2 \times w_2 + \ldots + \mathrm{r}_\mathrm{n} \times w_n \qquad (6)$$

where $w_1, w_2 \ldots, w_2$ represent the weights of criteria C_1 ,C_2,...,C_n obtained using AHP. The key performance for a scheme is assessed by the performance ranking of the index, which sorts the criteria from highest performing area of ITS to areas which perhaps require more focus.

4 M42 Case Study: description and primary data collection

4.1: Overview

In order to illustrate the data collection process, it is firstly necessary to define the scope of the infrastructure within the particular case study of the M42 ATM. The ATM features gantries spaced 500 metres apart and feature several components as illustrated by Figure 3 (future schemes may position these at 800 meters). Briefly, the infrastructure comprises a lightweight superspan gantry (covering 4-lanes), variable message signs, a HADECS camera enforcement unit, a set of four advanced motorway information (AMI) units over each carriageway and a combined equipment unit for each carriageway.

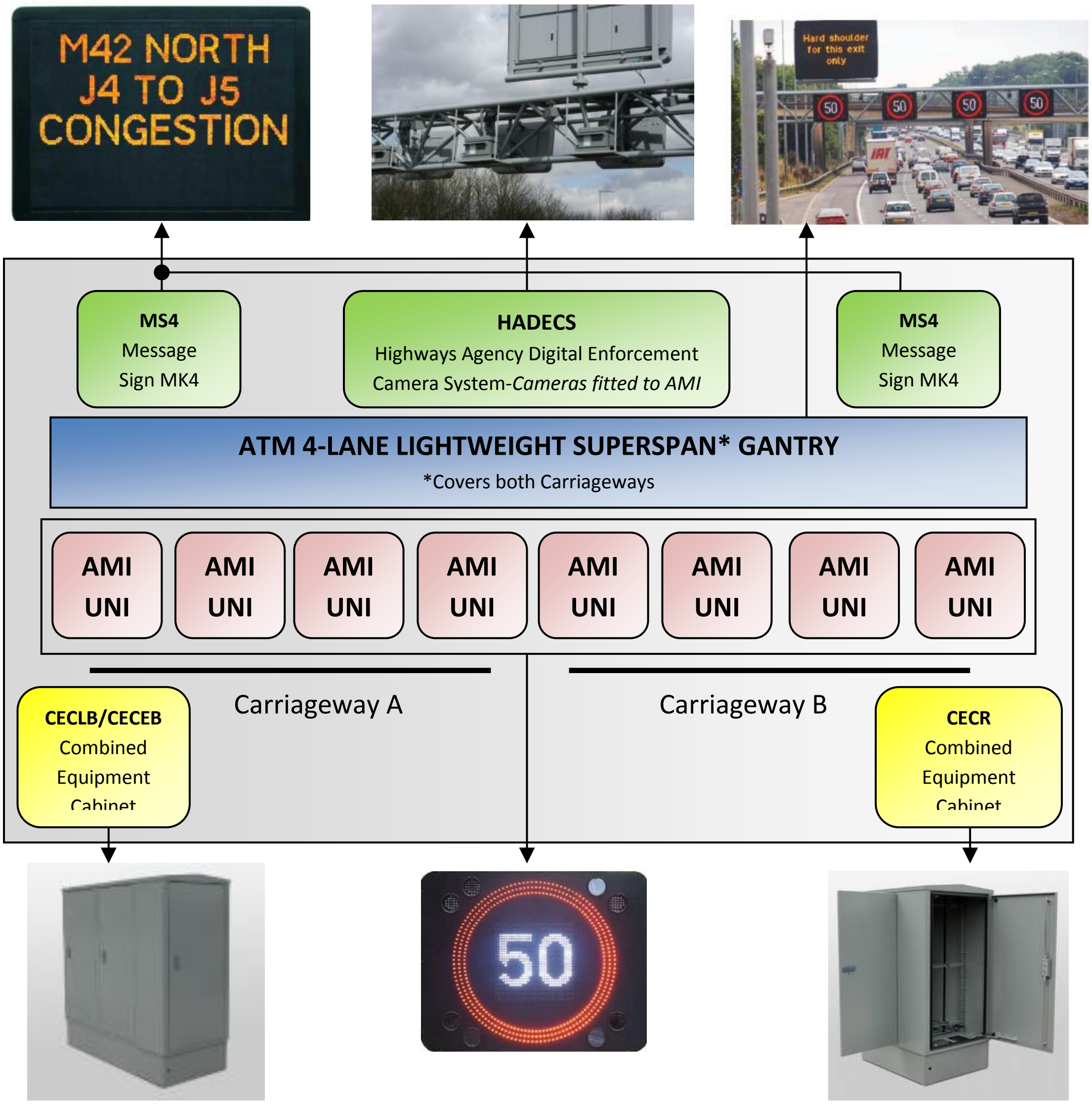

Figure 3: Typical ATM Gantry Inventory

The infrastructure is manufactured using a variety of materials, though the ATM performance specifications do not include a material and quantity guideline. Consequently, there is a large degree of uncertainty in terms of emissions across current ATM schemes. The data collection process was undertaken in two iterative stages, each stage involving the collection of primary and background data (see Figure 4).

Primary data collection involved liaison with the scheme component suppliers, and included: product schematics, material quantities, energy ratings for the output (message signs etc) and the logistics of the scheme (considering the journey time from the supplier to the site). The background data stage involved linking specific materials (collected from primary sources) to various processes throughout all stages of their lifecycle. This was undertaken using the Ecoinvent database which features pre-determined emissions categorisation on common (but not exhaustive) materials and process related energy use (Frischknecht et al, 2005; Frischknecht and Rebitzer, 2005).

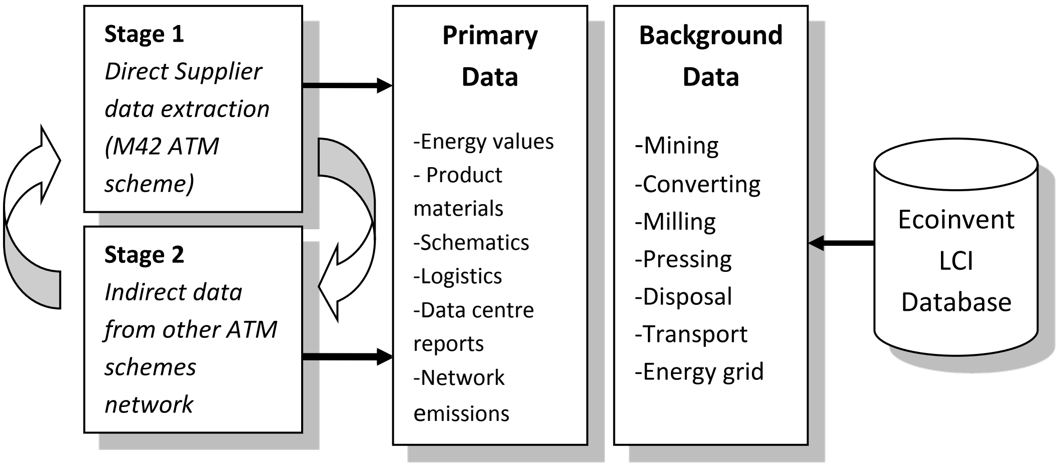

Figure 4: Data collection process

During the first stage, primary data were collected from four suppliers and the road network operator who were directly involved in the the M42 scheme. The second stage extended the geographical location of the data sources and included a further three suppliers plus two external consultants who operated on more recent ATM schemes within the UK network. This second stage was necessary to compensate for some restrictions in the availability of primary data from the M42 suppliers. This stage introduced some degree of uncertainty due to more recent versions of the ATM components coming into production and use in other schemes.

However, the extent of the component changes was judged not to be signficant for the purposes of this illustration.

4.2 Primary data: Standard Gantry

Primary data consisted of blueprints and specifications provided by the UK Road Network Operators Carbon Accounting Framework. Although construction of the infrastructure varies between sites and contractors, the ATM data for the M42 pilot is already available and therefore the choice for this study. Table 4 illustrates the Road Network Operators' estimated material weighting for each ITS component for a standard ATM highway section where (x) indicates no materials allocated to that piece of equipment.

ITS Equipment	Weight of Material per Unit (kg)						
	Steel	Reinforced Concrete	Copper	Aluminium	Toughened Glass	Plastics	Electrical Components
Lightweight SS Gantry	18,000	x	x	x	x	x	x
2*MS4 8*AMI	1,500	x	250	1,000	500	250	500
10 M Piles	x	16,000	x	x	x	x	x
Power Cable	0.7	x	1.8	x	x	0.5	x
Cabinets	30	2,000	1	x	x	2	20
Misc Cable	x	x	0.9	x	x	0.3	x
CCTV + Poles	200	1,000	x	2	x	x	2

Table 4: Standard Inter-Urban ATM Material Weighting

The data in Table 4 is considered generic for inter-urban ATM schemes and forms the second phase of the data collection as discussed below. It should be noted that there is a discrepancy as the Carbon Accounting Framework estimates the weight of a lightweight super span gantry at approximately 18,000 KG, whilst the LCA material analysis indicate a substantially higher weight at 39,083 Kg.

4.3 Primary data: Lightweight Superspan Gantry

Lightweight super span gantries are deployed in ATM schemes. These gantries extend over both carriageways and are produced using lightweight low alloyed steel.

The road network operator's supplier purchases semi-finished (uncoated) steel from up-stream suppliers within the European zone. Due to the lack of data on the production and conversion of the steel process, average data on the chemical composition and emissions of the graded steel product was collected using up-stream unit processes provided by the Swiss Ecoinvent database. This grading of steel derives solely from the chemical makeup and density of the primary production materials in the steel-making process. The total weight of the material is important in the calculation of the emissions as steel manufacturing is one of the most carbon intensive processes - despite attempts to curb its emissions by introducing more efficient production processes or alternative materials (Matsumiya, 2011; Yellishetty et al, 2011a; Yellishetty et al, 2011b). Because of the discrepancies of the total gantry weight between the road network operator and our own material weighting calculations, the data in Table 4 will be used for the purposes of illustration here. This is not to be confused with the use of Ecoinvent, rather it is to determine the actual weighting of components as part of the inventory analysis. The rationale is that the aggregation process is transparent and consistent with the supplier gantry schematics.

4.4 Primary data: Supporting Equipment

The materials assessed were very consistent with the ATM material weighting for Message Sign Mark 4 (MS4) and Advanced Motorway Indicators (AMI). Other components, such as the combined equipment cabinets required several estimations due to a lack of primary data. Combined equipment cabinets (CEC's) are used to store a variety of different hardware including power supplies, standard transponders, MIDAS (Motorway Incident Detection and Automatic Signalling) outstations, transponders and telephone responders along with other miscellaneous equipment associated with CCTV cameras (Highways Agency, 2009). There are three types of CEC available: The smallest cabinet - CEC-R ('Remote') sits on the side of the carriageway opposite the longitudinal power cable weighing 345 KG. Typically only MIDAS outstations and CCTV outstation equipment need to be housed on opposite carriageway to the longitudinal cable network. The CECR has one equipment bay with a power distribution bay located at one end. CEC-LB ('Longitudinal') is used on standard gantry locations and according to the supplier schematics weighs in at approx. 1,285 KG and is designed to house a longitudinal cable joint. The CEC-LB has a total of three equipment bays with the middle of the three housing the cable joints thus leaving two bays to house the electronic equipment. The power distribution bay is located at one end of the cabinet similar to the CECR.

Within enforcement areas the CECLB is replaced with the higher capacity CEC-EB (Enforcement) with an estimated steel casing weight of 1,600 KG. The largest Cabinet, the CEC-EB is designed to house the roadside controller for the Digital Enforcement Equipment as well as the normal highway communication and CCTV equipment.

4.5 Operational data assumptions

Various assumptions were made to determine the operational performance of the ATM system including energy consumption of electrical devices, maintenance and vehicle emissions (external to the LCA assessment). According to the road network operator’s implementation guidance (Highways Agency, 2009) the peak energy readings of the apparent electricity consumption (Volt-Amperes) was recorded on the M42 ATM between junctions 3A and 7 in 2006 with an average power factor of 0.9.

In addition to independent testing of signal power consumption, it was suggested that the gantry loads were approximately 11.7kVA (kilo Volts-Amperes) and a 10% reserve capacity of 12.8kVA. In order to determine the actual energy output of each device, further calculations were made. Table 5 illustrates these conversions applied to each ITS component within the scheme.

ITS Component	Sub-Component	Peak (VA) Apparent Power	Average Power Factor	Actual Power (kW)
Equipment Cabinet CECLB	Internal Lighting	80	0.9	0.072
	Heating and Cooling	2,200	0.9	1.980
	Maintenance Equipment	690	0.9	0.621
	Roadside Equipment	480	0.9	0.432
NRTS Load (Rectifiers -Backup)	N/A	2,500	0.9	2.250
Message Sign MK4	N/A	1,215	0.9	1.0935
Advanced Motorway Indicator	N/A	185	0.9	0.1665
Equipment Cabinet CECR	Internal Lighting	30	0.9	0.027
	Heating and Cooling	800	0.9	0.720
	Maintenance Equipment	690	0.9	0.621
	Roadside Equipment	280	0.9	0.252
	Total	**9,150**		**8.235**

Table 5: Energy conversion of standard ITS components

Based upon the apparent (VA) peak values from the implementation guidance, the correct value for the M42 ATM standard equipment is approx. 21 kW per km which increases to 29kW per km in enforcement areas with the addition of the Highways Agency Digital Enforcement Camera System and fixed CCTV. This does not include Advance Direction Signs and general lighting.

The operational phase of the scheme consists of temporary shoulder running operating during peak and off-peak times. During peak times, the power consumption is notably higher as the infrastructure guides vehicles onto the hard shoulder to increase network capacity. During off-peak, the majority of the infrastructure is on standby. The carbon accounting framework averages the typical consumption for a generic ITS service based on approximately 4,000 hours operation per annum (roughly 11 hours a day). Results from the Temporary Shoulder Use (Hard Shoulder Running in UK) 60 MPH evaluation (Ogawa et al, 2010) based upon a typical weekday indicate that 08:00-10:00 AM and 16:00-18:00 PM were the periods where the shoulder was active. It is assumed that the energy consumption within the equipment cabinets is active 24 hours a day. This equipment is used to monitor the performance of the components such as the MS4 sign and AMI units. This includes the National Road Transmission Service load which features a constantly charged battery for backup or disaster avoidance. According to the implementation guidance the MS4 and AMI units are on standby under normal running operations but become active during the morning and afternoon peaks.

From these assumptions it is possible to forecast the daily, annual and lifespan[ii] (15 years) energy consumption of the post 2005 ATM ITS equipment. The value for the total lifespan of an individual gantry is based upon the individual ITS components operational performance over 15 years and was integrated into the lifecycle using upstream energy production scenarios in the Ecoinvent database. Although a typical scheme predicates to 30 years, a great deal of uncertainty would be introduced into the model if the lifespan was extended due to a need to assess increasing energy efficiency in technological advancement of infrastructure components (Mathiesen et al, 2009; Lund et al, 2010). From Figure 5, the energy requirements of a standard gantry is illustrated. Enforcement locations require additional equipment such as the Highways Agencies Digital Enforcement Camera System and a large equipment cabinet is required for this purpose (replacing the CEC-LB). Advanced direction signage requires lighting in some locations and will increase the power consumption.

The right hand diagram illustrates corresponding calculations for the entire (16.4km) scheme (M42, junctions 3a to 7) with each gantry configuration. As the data concerning the ratio of enforced to standard gantry locations is unavailable, only the standard energy consumption was modelled using the LCA, although the diagram illustrates the results of the energy consumption if the complement of each gantry configuration was at 100% for the whole scheme.

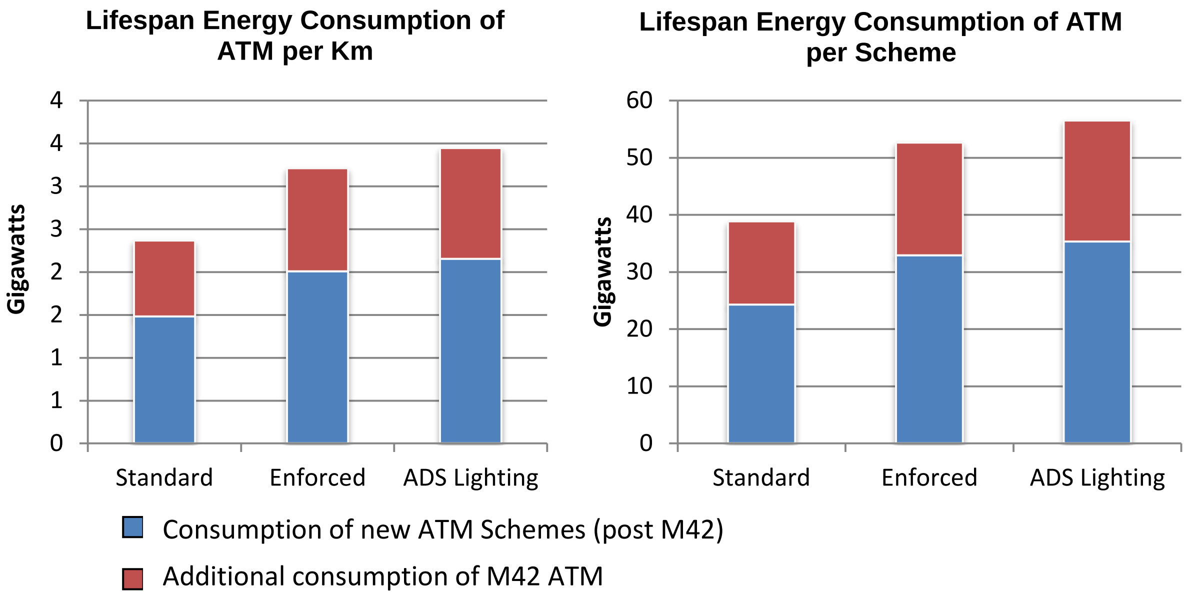

Figure 5: Energy consumption by scheme type (left: per KM, right: Full scheme)

The consumption of new ATM differs from the M42 pilot due to the spacing of each gantry which is 800 metres while the M42 features gantries spaced at 500 metres. Following collection of all the necessary primary data for the scheme infrastructure, the EnvFUSION method could then be applied as described in Section 5 below.

5 M42 Case Study: application of EnvFUSION methodology

This section illustrates the application of the EnvFUSION methodology as described in section 3 for the M42 Case Study and using the primary data outlined in section 4.

It should be noted that the method is generic and with the correct data, similar schemes internationally may also use this methodology.

5.1 System boundary, criteria allocation and assignment

The system boundary of the study is an assessment of ATM infrastructure per km multiplied by the scheme length over its lifecycle (from 2005 to 2020) using an attributional LCA. The midpoint method of the LCA calculates the greenhouse gas (GHG) emissions as KG CO_2 equivalency of the scheme per kilometre, using ratio parameters taken from the road network operators' Carbon Accounting Framework created in 2008. ICT operational data was obtained by direct observation from the local traffic control centre. Vehicle road emissions were calculated from the Department for Transports National Transport Model emission curves (AEA, 2009). The criteria selected (Figure 2) represent all elements for estimating ITS sustainability and include Scheme lifecycle emissions (C_1), Road user emissions (C_2), Kg of CO2 covered by IT certificates (C_3), KG of CO_2 per IT task or resource (C_4), Energy used per task or resource (C_5), Annual DCIE for data center (C_6), Roadside energy consumption (C_7), Acceptance (C_8), Safety (C_9) and Scheme cost (C_{10}). The Road network operator provided equal weights (=0.100) to the criteria using AHP.

5.2 LCA Emissions Results

The LCA emissions were determined in the impact assessment phase using the LCA impact method developed by the Center of Environmental Science of Leiden University (CML). The results in this paper are displayed in CO_2 equivalency using the Global Warming Potential (GWP) method, a relative measure of how much heat a greenhouse gas traps in the atmosphere, calculating the lifecycle of emissions in the atmosphere over a 100 year period.

Normalisation and damage assessment factors were ignored due to the emissions data subsequently acting as direct input to the EnvFUSION endpoint method using AHP/DST theory. Figure 6 illustrates the lifecycle (2006-2020) contribution of the vehicle emissions, ICT emissions and ATM infrastructure embedded emissions in Kilo-tonnes of CO2 equivalency. The GWP of the schemes energy consumption is also included and is largely accountable for the increase in emissions from ATM. Note that the ICT emissions remain constant - this is due to the road network operator not possessing the required measuring equipment for estimating data center energy workload per km of the scheme.

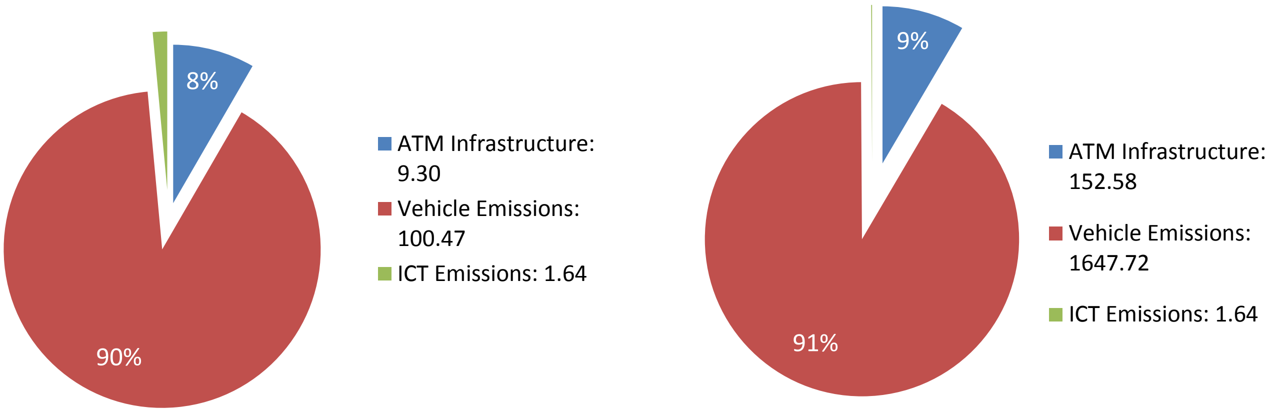

Figure 6: Overall GWP of ATM in ktCO2eqv (Left: Per KM, Right: Per Scheme)

5.2.1 ATM Infrastructure Emissions

Estimated emissions results for individual ITS components are outlined below. The value is in tonnes of CO2 equivalent over a 100 year GWP time horizon and the temporal boundary of the study is set at 15 years taking into account the full cradle-to-grave assessment up to 2020. Operational assumptions include the total energy consumption for the infrastructure in addition to the maintenance of the electrical components.

Table 6 illustrates the distribution of GHG emissions of gantry and supporting infrastructure per KM within the M42 managed motorway scheme for the 15 year period to 2020. Note that support includes the power infrastructure and any additional enforcement equipment such as CCTV etc. A more detailed breakdown is unavailable due to the confidentiality agreement in place for the research between the road network operators and research team. The main results feature the spacing of each gantry on the M42 at 500 metres while the results in brackets indicate the difference in emissions of more recent ATM schemes (post M42) at 800 metres.

GHG Substance in KG CO2eqv (800 metre spacing in brackets for ATM post M42)	**Lightweight Gantry**	**Message Sign MK4**	**CECLB Equip. Cabinet**	**CECR Equip. Cabinet**	**AMI**	**Support (CCTV etc)**
Carbon dioxide, fossil	266,572 (166,607)	1,376,868 (860,542)	968,566 (605,354)	785,764 (491,103)	4,980,448 (3,112,780)	362,994 (226,871)
Methane, fossil	14,956 (9,347)	56,202 (35,126)	46,778 (29,236)	37,994 (23,746)	201,008 (125,630)	340,262 (212,664)
Dinitrogen monoxide	1,346 (841)	12,570 (7,856)	9,916 (6,197)	8,082 (5,051)	45,454 (28,409)	15,668 (9,793)
Ethane, hexafluoro-, HFC-116	22 (14)	10,172 (6,357)	296 (185)	152 (95)	27,746 (17,341)	4,116 (2,573)
Sulfur hexafluoride	286 (179)	5,274 (3,296)	6,296 (3,935)	1,950 (1,219)	17,874 (11,171)	116 (73)
Methane, tetrafluoro-, CFC-14	92 (57)	16,482 (10,301)	180 (112)	108 (68)	10,134 (6,334)	1,758 (1,099)
Carbon monoxide, fossil	3,672 (2,295)	3,562 (2,226)	756 (472)	468 (293)	8,162 (5,101)	230 (144)
Methane, biogenic	314 (196)	1,022 (639)	110 (69)	78 (49)	4,112 (2,570)	676 (423)
Methane, chlorodifluoro-, HCFC-22	8 (5)	640 (400)	44 (27)	28 (18)	2,564 (1,603)	92 (58)
Carbon dioxide, land transformation	8 (5)	332 (207)	82 (51)	64 (40)	1,306 (816)	24 (15)
Remaining Substances	3,476 (2,172)	40 (25)	646 (404)	98 (61)	72 (45)	2,584 (1,615)
TOTAL OF ALL COMPARTMENT	287,316 (179,573)	1,483,776 (927,360)	1,033,124 (645,702)	834,764 (521,728)	5,301,392 (3,313,370)	362,994 (226,871)
GANTRY INSTALLATION	19 (12) Tonnes of CO_2 including all gantry equipment and support					
GANTRY DECOMISSION	19 (12) Tonnes of CO_2 including all gantry equipment and Support					

Table 6: KG CO_2 Equivalency of GHG substances for ATM infrastructure per KM up to 2020

5.2.2 Vehicle Emissions

Using polynomial regression, annual average daily traffic flows (AADF) on the M42 were forecast along with vehicle emissions curves and predicted vehicle market share from the national transport model (which projects future emissions by vehicle types up to 2035). Lifespan vehicle emissions were based upon the annual average daily traffic flows that were recorded from five count points over two 12 hour periods per day ($AADF_{CP}$) multiplied by the link length of the scheme $Length_{link}$ and the number of days in the year using equation (7).

$$Traffic_{CP} = AADF_{CP} \times Length_{link} \times 365 \tag{7}$$

Projected vehicle composition factors were taken from the UK's National Atmospheric Emissions Inventory (NAEI, 2012) while speed/emission curves were extracted from the National Transport Model (AEA, 2009). Table 7 illustrates the resulting vehicle emissions over a period of 15 years in tonnes of CO_2 equivalency. Average speeds across the M42 were extrapolated up to 2020. Note that for cars, taxis and light goods vehicles; petrol and diesel emissions are combined.

Greenhouse Gas Substance (Tonnes CO_2 Equiv.)	**2 Wheeled Motor Vehicles**	**Cars and Taxis**	**Coaches**	**Light Goods Vehicle**	**Heavy Goods Vehicle**
All Operational Regimes (24 hour)					
Carbon monoxide (CO)	252	3,978	17	184	576
Nitrous Oxide (NOx (Equivalent of $N0_2$)	18	2,291	124	611	4,548
Hydrocarbons (Equivalent of $CH_{1.85}$)	21	261	4	33	116
Ultimate Carbon Dioxide (CO_2)	2,874	534,191	17,359	24,728	1,005,101
All Compartments	3,165	540,721	17,504	25,556	1,010,341
Temporary Shoulder Running (HSR 60) at Morning and Afternoon Peak					
Carbon monoxide (CO)	52	829	4	39	120
Nitrous Oxide (NOx Equivalent of $N0_2$)	4	477	26	127	947
Hydrocarbons (Equivalent of $CH_{1.85}$)	5	54	1	6	24
Ultimate Carbon Dioxide (CO_2)	599	111,289	3,616	5,151	209,396
All Compartments	660	112,649	3,647	5,323	210,487

Table 7: Tonnes CO_2eqv for M42 Junction 3A-7 vehicle emissions up to 2020

Figure 7 represents the cumulative savings of emissions in Global Warming Potential post implementation up to 2020. From this analysis, it could be concluded that (in terms of a traditional Environmental Impact Assessment) the vehicle emissions within the ATM scheme - along with the minor advantages of improved traffic flow - will offset their emissions by the end of the scheme lifespan, taking into account the roadside infrastructure. Projecting the results of the highways agencies emissions monitoring between 2003 and 2006 (traffic growth fixed at 2003 levels), an estimated 53 kilo-tonnes of CO_2 equivalency will be offset by 2020 due to the direct usage of the ATM scheme.

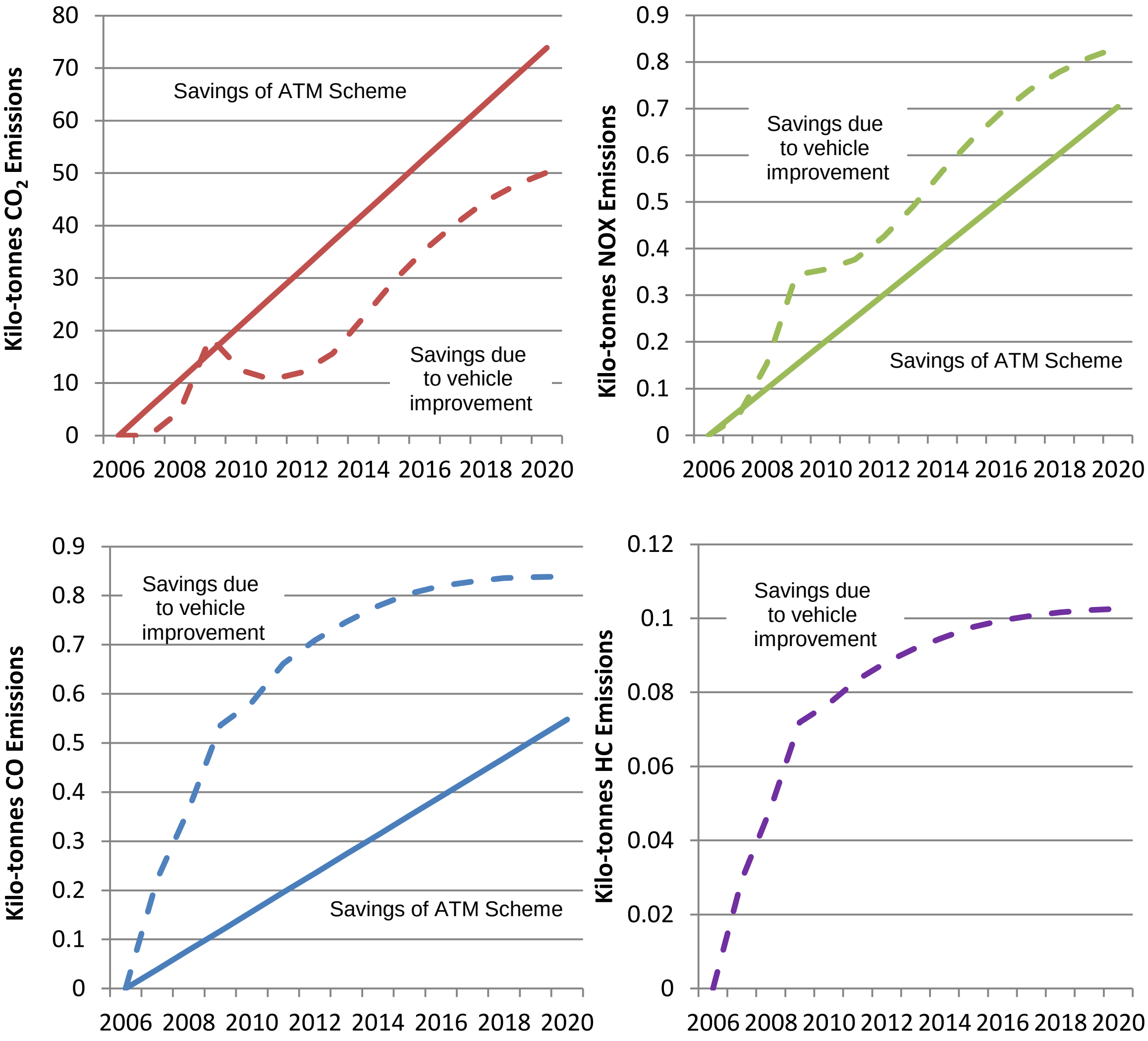

Figure 7: Vehicle Emission Cumulative Savings of GHG's

Savings due to estimated improvements in vehicle technology are also illustrated which are dependent on traffic growth and follow assumptions of the UK's National Transport Model (AEA, 2009). See Sultan (2009) for more detailed results on the M42 ATM monitoring and evaluation process. Between 2003-2006, Hydrocarbon emissions increased by 3%. It is possible that the increase in HC emissions is due to the change in vehicle operation, *i.e.* the engines are operating in an area that is less efficient with regards to HC emissions and is an area that requires further investigation (Sultan, 2009). Whilst the speed limit for temporary shoulder use was initially set at 80 Km/h (50 Mp/h), by 2008 it was increased to 97 Km/h (60 Mp/h). This resulted in an increase in average traffic speed by 8 Km/h. Traffic growth between the case of no variable speed enforcement and the case of full VSM enforcement plus temporary shoulder usage has increased by 6% (northbound) and 9% (southbound). This increase is in-line with national highway traffic growth of 7.9% (Figure 8).

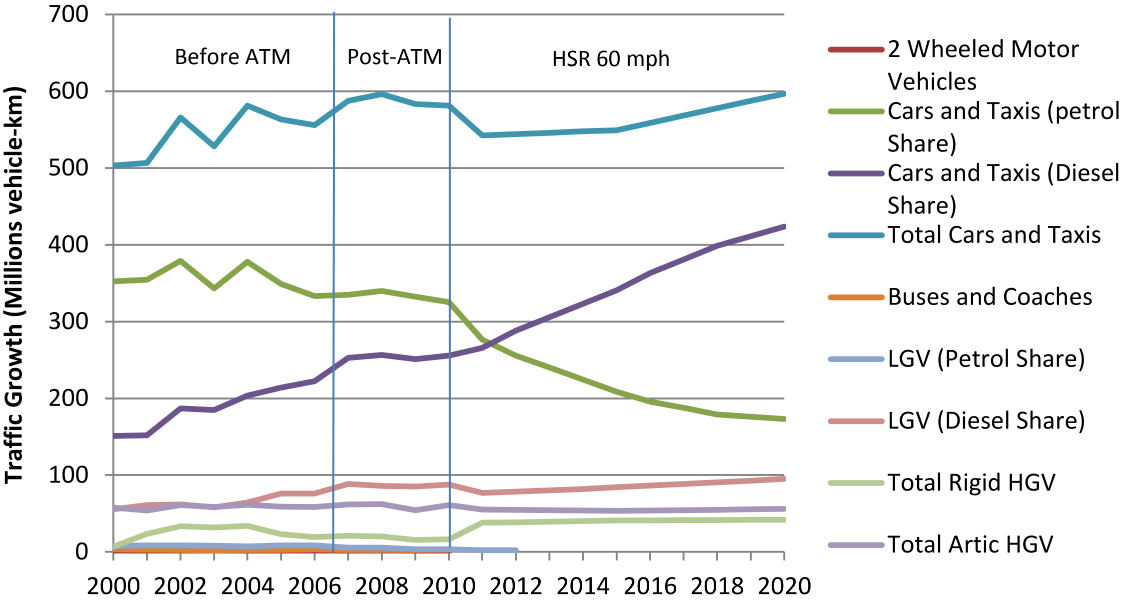

Figure 8: M42 J3A-7 Annual Traffic Growth

5.2.3 ICT Data Emissions

Data for ICT Emissions from the ATM scheme were taken from the regional traffic control centre responsible for its operation. Following direct observation of the data center, communication interface and an interview with staff, Table 8 illustrates the current environmental status of the regional traffic control center.

Parameters/Criteria	***Result***
Energy used for task or resource	185,747 KWh per Annum (2,786,205 lifespan)
GWP per task or resource	109,163 KG CO2eqv (1,637,453 lifespan)
GWP offset	None
Kg of CO2 covered by renewable energy certificates	None
What is your annualized average PUE (last 12 months)	2.5
Are you European Code of Conduct for Datacenter compliant?	No
Do you have an Energy Star for Datacenter rating	No
Are you LEED (or BREEAM) for data center rated?	No

Table 8: ICT Environmental Status of Regional Traffic Control Center

Due to current limitations in ICT metrics, the energy per task and resource could only be assessed at the hardware level, and although various research initiatives are being carried out to understand the energy consumption at the application/software level (Berl et al, 2010), the regional traffic control center does not have the required technology to overcome these constraints at the time of writing.

5.2.4 Uncertainty Assessment and Assumptions

As outlined in (3.3) the Ecoinvent database addresses uncertainty in the data using the Ecoinvent logarithmic distribution (Frischknecht and Rebitzer, 2005). All unit processes have six embedded factors of uncertainty factors comprising: reliability, completeness, temporal correlation, geographical correlation, further technological correlation and finally sample size (calculated using a Petri matrix). Uncertainty in EnvFUSION is addressed in several stages. Firstly, 1000 Monte Carlo simulations were performed on the LCA inventory to determine the absolute uncertainty of the lifecycle of a gantry. Figure 10 illustrates the absolute uncertainty distribution of the lifecycle inventory with global warming potential. The horizontal axis displays the value of the calculation while the vertical axis represents the probability that a certain value is true, with the confidence interval calculated using equation (1). It can be seen from Figure 9 that the overall emissions may be higher than the initial calculation based upon the six uncertainty factors, although the probability distribution is negatively skewed overall, with higher probabilities assigned to the lower levels of emission values. Figure 10 illustrates global warming potential uncertainty compared with the uncertainty of other environmental factors in the LCA inventory.

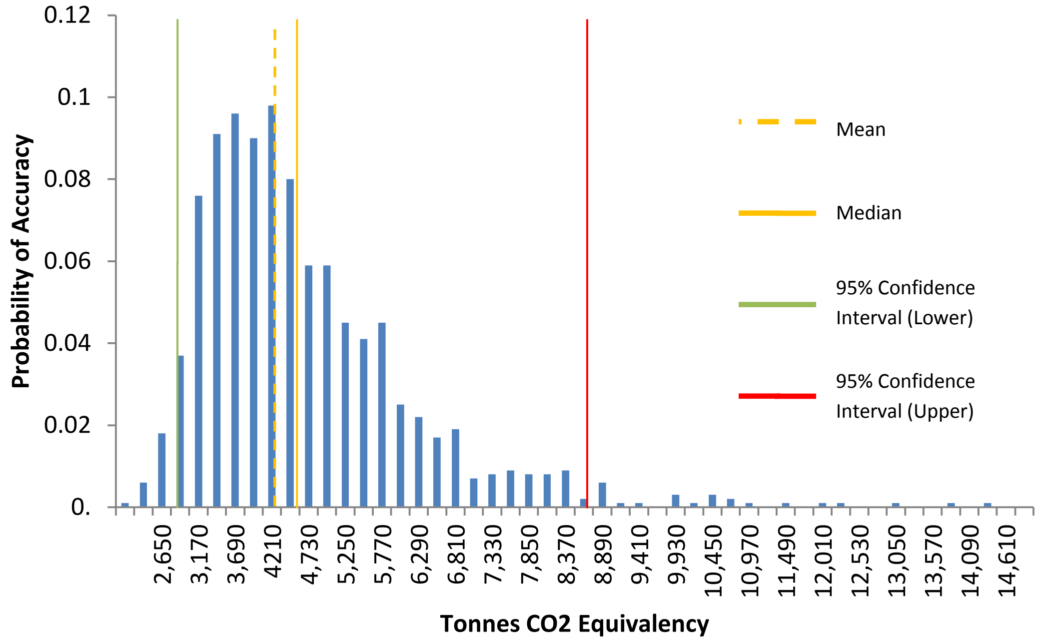

Figure 9: Lifecycle emissions uncertainty: Global Warming Potential (GWP 100)

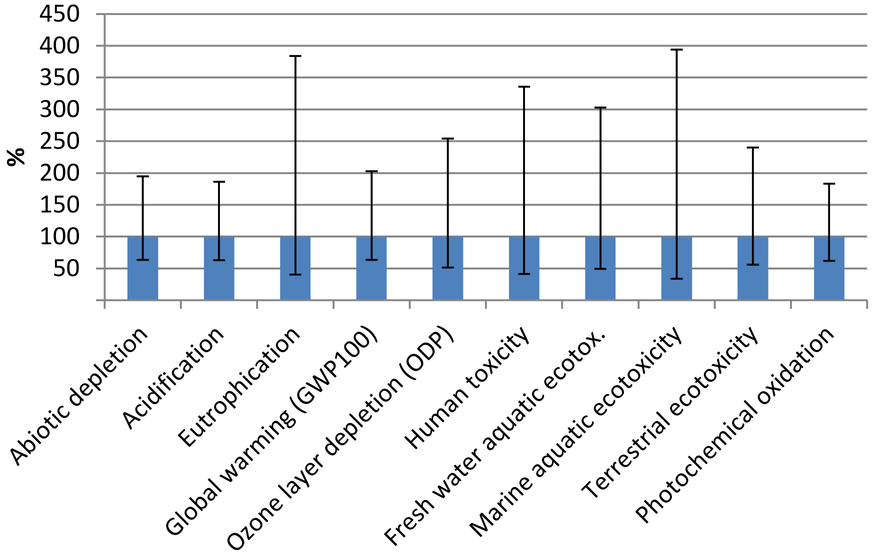

Figure 10: Comparison of Lifecycle characterisation uncertainty

From Figure 10, Global Warming Potential has one of the lowest levels of uncertainty when compared to other characterisation factors. Although these other factors do not contribute to the EnvFUSION model, they are illustrated in order to reflect the wider environmental uncertainty within the ATM scheme.

5.3 Data Fusion and Indicator Estimation

Data collection[iii] was carried out using four sources, i.e. Experts (source 1), the LCA model (source 2), ICT metrics (source 3) and reports (source 4). The sources generated data on BPA's (or mass values (m) in the case of missing data) concerning six performance levels (No Target (N), Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH)). The layout for calculating Dempster-Shafer is motivated by Awasthi and Chauhan (2011).

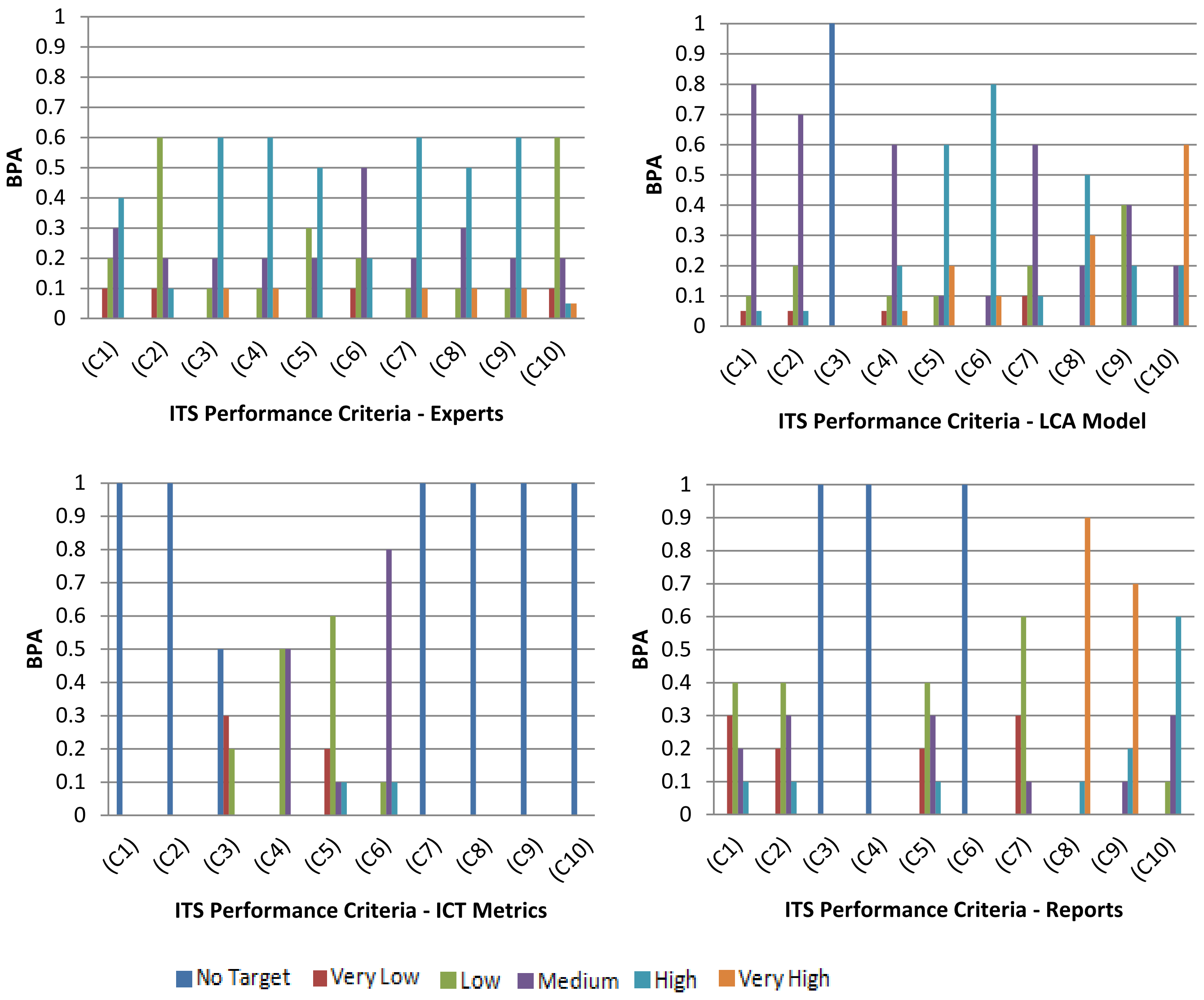

Figure 11: ITS Sustainability BPA Assignments

Figure 11 illustrates the BPA values from each source for the following criteria: Scheme lifecycle emissions (C1), Road User Emissions (C2), GWP Data Center Offset (C3), GWP per IT resource (C4), Energy Used Per Resource (C5), Annual DCIE/PUE for data center (C6), Road side energy consumption (C7), Acceptance (C8), Safety (C9) and Scheme Cost (C10). An example is given below for one criteria - 'scheme lifecycle emissions' to demonstrate the fusion process for the data sources. For the Experts information source, the probabilities are:

$NT = 0$, $VL = 0$, $L = 0.3$, $M = 0.3$, $H = 0.4$ and $VH = 0$.

In the first stage information source 1 and 2 were combined. In the second stage the results from stage 1 were combined with information source 3. In the final stage, the results were combined with stage 2 and information source 4. The criteria 'Scheme lifecycle emissions' is calculated based on the distance to target method. The bpa values are denoted as follows: from *Experts* by m_1^1, from the *LCA Model* by m_2^1, from the *ICT Metrics* by m_3^1 and from *Reports* by m_4^1. The following calculations are taken from figure 12.

$m_1^1(NT) = 0, m_1^1(VL) = 0.1, m_1^1(L) = 0.2, m_1^1(M) = 0.3, m_1^1(H) = 0.4, m_1^1(VH) = 0$

$m_2^1(NT) = 0, m_2^1(VL) = 0.05, m_2^1(L) = 0.1, m_2^1(M) = 0.8, m_2^1(H) = 0.05, m_2^1(VH) = 0$

$m_3^1(NT) = 1, m_3^1(VL) = 0, m_3^1(L) = 0, m_3^1(M) = 0, m_3^1(H) = 0, m_3^1(VH) = 0$

$m_4^1(NT) = 0, m_4^1(VL) = 0.3, m_4^1(L) = 0.4, m_4^1(M) = 0.2, m_4^1(H) = 0{,}1, m_4^1(VH) = 0$

Table 9 presents the fusion[iv] results from source 1 (Expert) and source 2 (Models). Numbers are rounded for clarity and for conciseness, those columns and rows of the combination were dropped which do not have assigned values.

	$m_1^1(NT) = 0$	$m_1^1(VL) = 0$	$m_1^1(L) = 0.1$	$m_1^1(M) = 0.2$	$m_1^1(H) = 0.3$	$m_1^1(VH) = 0.4$	$m_1^1(\Theta) = 0$
$m_2^1(VL) = 0.05$	ϕ 0	(VL) 0	ϕ 0.005	ϕ 0.001	ϕ 0.015	ϕ 0.02	(VL) 0
$m_2^1(L) = 0.1$	ϕ 0	ϕ 0	(L) 0.01	ϕ 0.02	ϕ 0.03	ϕ 0.04	(L) 0
$m_2^1(M) = 0.8$	ϕ 0	ϕ 0	ϕ 0.08	(M) 0.16	ϕ 0.24	ϕ 0.32	(M) 0
$m_2^1(H) = 0.05$	ϕ 0	ϕ 0	ϕ 0.01	ϕ 0.01	(H) 0.03	ϕ 0.02	(H) 0
$m_2^1(\Theta) = 0$	(NT) 0	(VL) 0	(L) 0	(M) 0	(H) 0	(VH) 0	ϕ 0

Table 9: Data Fusion from information sources 1 and 2

$$k = 0.005 + 0.08 + 0.01 + 0.001 + 0.02 + 0.01 + 0.015 + 0.03 + 0.24 + 0.02 + 0.04 + 0.32 + 0.02 = 0.73 > 0$$

Since k > 0, normalisation was applied where the normalisation factor is given by 1 - k = 1 - 0.715 = 0.285. The main results of the first stage fusion between information source 1 and 2 can be expressed as:

$m_1^1 \oplus m_2^1(NT) = \frac{0}{0.285} = 0,\ m_1^1 \oplus m_2^1(VL) = \frac{0}{0.285} = 0.017, m_1^1 \oplus m_2^1(L) = \frac{0}{0.285} = 0.070$

$m_1^1 \oplus m_2^1(M) = \frac{0.24}{0.285} = 0.842,\ m_1^1 \oplus m_2^1(H) = \frac{0.03}{0.285} = 0.070, m_1^1 \oplus m_2^1(VH) = \frac{0.03}{0.285} = 0$

$m_1^1 \oplus m_2^1(\Theta) = 0$

The next step is to combine the results from information fusion between source 1 (Expert) and 2 (Model) with information source 3 (Survey) in Table 10.

	$m_3^1(NT) = 1$	$m_3^1(VL) = 0$	$m_3^1(L) = 0$	$m_3^1(M) = 0$	$m_3^1(H) = 0$	$m_3^1(VH) = 0$	$m_3^1(\Theta) = 0$
$m_1^1 \oplus m_2^1(VL) = 0.0017$	ϕ 0.01754	(VL) 0	ϕ 0	ϕ 0	ϕ 0	ϕ 0	(VL) 0
$m_1^1 \oplus m_2^1(L) = 0.070$	ϕ 0.07017	ϕ 0	(L) 0	ϕ 0	ϕ 0	ϕ 0	(L) 0
$m_1^1 \oplus m_2^1(M) = 0.842$	ϕ 0.84210	ϕ 0	ϕ 0	(M) 0	ϕ 0	ϕ 0	(M) 0
$m_1^1 \oplus m_2^1(H) = 0.070$	ϕ 0.07017	ϕ 0	ϕ 0	ϕ 0	(H) 0	ϕ 0	(H) 0
$m_1^1 \oplus m_2^1(\Theta) = 0$	(NT) 0	(VL) 0	(L) 0	(M) 0	(H) 0	(VH) 0	ϕ 0

Table 10: Data Fusion from information sources 1 and 2 and 3

$$k = 0.01754 + 0.07017 + 0.84210 + 0.07017 = 1$$

Since k = 1, the source is totally contradictory therefore normalisation is not applied (orthogonal sum is ignored therefore removing the source from the fusion process). This is justified as the ICT Metric does not have a target for the 'scheme lifecycle emissions'. With the results from the first fusion unchanged, the next stage of the fusion process is carried out. In Table 11, the results were combined from information sources 1, 2 and 3 with information source 4.

	$m_4^1(NT) = 0$	$m_4^1(VL) = 0.3$	$m_4^1(L) = 0.4$	$m_4^1(M) = 0.2$	$m_4^1(H) = 0.1$	$m_4^1(VH) = 0$	$m_4^1(\Theta) = 0$
$m_1^1 \oplus m_2^1 \oplus m_3^1(VL) = 0.0017$	ϕ 0	(VL) 0.0052	ϕ 0.0028	ϕ 0.0035	ϕ 0.0017	ϕ 0	(VL) 0
$m_1^1 \oplus m_2^1 \oplus m_3^1(L) = 0.0701$	ϕ 0	ϕ 0.0210	(L) 0.0280	ϕ 0.0140	ϕ 0.0070	ϕ 0	(L) 0
$m_1^1 \oplus m_2^1 \oplus m_3^1(M) = 0.8421$	ϕ 0	ϕ 0.2526	ϕ 0.3368	(M) 0.1684	ϕ 0.0842	ϕ 0	(M) 0
$m_1^1 \oplus m_2^1 \oplus m_3^1(H) = 0.0701$	ϕ 0	ϕ 0.0210	ϕ 0.0280	ϕ 0.0140	(H) 0.0070	ϕ 0	(H) 0
$m_1^1 \oplus m_2^1 \oplus m_3^1(\Theta) = 0$	(NT) 0	(VL) 0	(L) 0	(M) 0	(H) 0	(VH) 0	ϕ 0

Table 11: Data Fusion from all sources (1, 2, 3 and 4)

$$\begin{aligned} k = {} & 0.0210 + 0.2526 + 0.0210 + 0.0028 + 0.3368 + 0.0280 + 0.0035 \\ & + 0.0140 + 0.0140 + 0.0017 + 0.0070 + 0.0842 = 791288 > 0 \end{aligned}$$

Since k > 0, normalisation was applied where the normalisation factor is given by 1 - k = 1 - 0.791288 = 0.208772. The main results of the final stage fusion between information source 1, 2, 3 and 4 can be expressed as:

$$m_1^1 \oplus m_2^1 \oplus m_3^1 \oplus m_4^1\ (VL) = \frac{0.005263}{0.208772} = 0.025210084$$

$$m_1^1 \oplus m_2^1 \oplus m_3^1 \oplus m_4^1\ (L) = \frac{0.02807}{0.208772} = 0.134453782$$

$$m_1^1 \oplus m_2^1 \oplus m_3^1 \oplus m_4^1\ (M) = \frac{0.168421}{0.208772} = 0.806722689$$

$$m_1^1 \oplus m_2^1 \oplus m_3^1 \oplus m_4^1\ (H) = \frac{0.007018}{0.208772} = 0.033613445$$

$$m_1^1 \oplus m_2^1 \oplus m_3^1 \oplus m_4^1\ (\Theta) = 0$$

It is assumed that the reliability of each information source is 1. Therefore from Appendix A equation (9):

$m^{\alpha}(NT) = 0,\ m^{\alpha}(VL) = 0.025210084\ ,\ m^{\alpha}(L) = 0.134453782,\ m^{\alpha}(\mathrm{M}) = 0.806722689$

$m^{\alpha}(H) = 0.033613445,\ m^{\alpha}(VH) = 0,\ m^{\alpha}(\Theta) = 0$

Using the DST rule set and $m\ (\emptyset) = 0$ the bpa's were obtained for the criteria 'scheme lifecycle emissions' as follows:

$$m^{\alpha}(NT) = \left(\frac{1}{1}\right) \times \left(\frac{0}{1}\right) = 0$$

$$m^{\alpha}(VL) = \left(\frac{1}{1}\right) \times \left(\frac{0.025210084}{1}\right) = 0.025210084$$

$$m^{\alpha}(L) = \left(\frac{1}{1}\right) \times \left(\frac{0.134453782}{1}\right) = 0.134453782$$

$$m^{\alpha}(M) = \left(\frac{1}{1}\right) \times \left(\frac{0.134453782}{1}\right) = 0.806722689$$

$$m^{\alpha}(H) = \left(\frac{1}{1}\right) \times \left(\frac{0.033613445}{1}\right) = 0.33613445$$

$$m^{\alpha}(\Theta) = \left(\frac{1}{1}\right) \times \left(\frac{0}{6}\right) = 0$$

The bpa's for the criteria 'scheme lifecycle emissions' are obtained once all elements of the data sources have been fused. The calculations were then carried out for the remaining 9 criteria from Figure 11. Table 12 illustrates the bpa's of the criteria after data fusion.

Performance Criteria	Sustainability Grade BPA					
	NT	*VL*	*L*	*M*	*H*	*VH*
Scheme lifecycle emissions (C_1)	0	0.02521	0.13445	0.80672	0.03361	0
Road User Emissions (C_2)	0	0.01092	0.52459	0.45901	0.00546	0
Kg of CO2 off - IT certificates (C_3)	0	0.62791	0.37209	0	0	0
KG of CO_2 per IT resource (C_4)	0	0	0.07692	0.92307	0	0
Energy used per resource (C_5)	0	0	0.66666	0.05556	0.27778	0
Annual DCIE for data center (C_6)	0	0	0	0.71428	0.28571	0
Roadside Energy Consumption (C_7)	0	0	0.5	0.5	0	0
Acceptance (C_8)	0	0	0	0	0.48076	0.51925
Safety (C_9)	0	0	0	0.85714	0.14285	0
Scheme Cost (C_{10})	0	0	0	0	0.05263	0.94736

Table 12: BPA values following data fusion

The overall performance ranking was then computed using the performance grades from table 3 and distance to target weights that are specific to the M42. These were derived using the process outlined in section 3.4 and provided in Table 13 below.

Sustainability Criteria	*Apparent Sustainability burden (2006)*	*Future Target (2020)*	*Preliminary Distance-To-Target Value*	*DTT Weight*
Scheme lifecycle emissions (tCO2eqv)	10,171	5,000	5,171	0.5
Road user emissions (tCO2eqv)	106,486	40,000	66,486	0.6
GWP Data center offset (kgCO2eqv)	0	0	0	0.1
GWP per IT resource (kgCO2eqv)	1,637	1,000	637	0.6
Energy used per resource (Mw/h)	2,786	2,000	786	0.7
Annual DCIE/PUE for data center (%)	2.5	2.0	0.5	0.8
Roadside energy consumption (Mw/h)	2588	1200	1300	0.5
Acceptance (%)	97 Shoulder	100 Shoulder	03 Shoulder	1.0
Safety (KSR ratio-4VMSL)	7	6	1	1.0
Scheme cost (Millions/£)	96	96	0	1.0

Table 13: Distance to Target weights for the M42 case study

For example, the overall performance ranking for the criteria "scheme lifecycle emissions" is calculated as follows:

$$r_i \begin{cases} = r(NT) \times bpa(NT) + \ r(VL) \times bpa(VL) + \ r(L) \times bpa(L) \\ + r(M) \times bpa(M) + \ r(M) \times bpa(M) + \ r(H) \times bpa(H) + \\ + r(VH) \times bpa(VH) \ \times \ DTT \\ = 0.3 \ \times 0.02521 \ + 0.5 \ \times 0.13445 \ + 0.7 \ \times \ 0.80672 \\ +0.9 \ \times 0.03361 \ \times 0.5 \ = 0.133948 \end{cases}$$

The overall sustainable performance ranking, distance to target weights and AHP were then calculated for the remaining 9 criteria as shown in Table 14.

Performance Criteria	Calculation of Intelligent Transport Sustainability Index				
	GPR	*BPA's*	*DTT weighting*	*AHP*	*ITSI Value*
Scheme lifecycle emissions (C_1)	0.3 X	VL= 0.02521	X 0.5	X 0.100	0.033487
	0.5 X	L= 0.13445			
	0.7 X	M= 0.80672			
	0.9 X	H= 0.03361			
Road User Emissions (C_2)	0.3 X	VL= 0.01092	X 0.6	X 0.100	0.035508
	0.5 X	L= 0.52459			
	0.7 X	M= 0.45901			
	0.9 X	H= 0.00546			
GWP Data offset - IT certificates (C_3)	0.3 X	VL= 0.62791	X 0.1	X 0.100	0.002656
	0.5 X	L= 0.37209			
GWP per IT resource (C_4)	0.5 X	L = 0.07692	X 0.6	X 0.100	0.041077
	0.7 X	M = 0.92307			
Energy used per resource (C_5)	0.5 X	L= 0.66666	X 0.7	X 0.100	0.069028
	0.7 X	M= 0.55556			
	0.9 X	H= 0.27778			
Annual DCIE/PUE for data center (C_6)	0.7 X	M= 0.71428	X 0.8	X 0.100	0.060571
	0.9 X	H= 0.28571			
Roadside Energy Consumption (C_7)	0.5 X	L= 0.50000	X 0.5	X 0.100	0.030000
	0.7 X	M= 0.50000			
Acceptance (C_8)	0.9 X	H= 0.48076	X 1.0	X 0.100	0.095193
	1.0 X	VH = 0.51925			
Safety (C_9)	0.7 X	M= 0.85714	X 1.0	X 0.100	0.090000
	0.9 X	H= 0.14285			
Scheme Cost (C_{10})	0.7 X	M= 0.05263	X 1.0	X 0.100	0.099474
	0.9 X	H= 0.94736			

Table 14: Intelligent Transport Sustainability Index calculations

5.4 The Intelligent Transport Sustainability index

Using the calculations shown in Table 14 and criteria weights, the Intelligent Transport Sustainability Index (ITSI) is finally generated. The ITSI index brings together the fused performance targets, the DTT method and AHP, resulting in an overall distribution of criteria priorities. Although the apparent performance grades are ranked subjectively, the distance to target weights reflect quantitative governmental targets.

Performance Criteria	Final ITSI Index Results		
	Apparent Performance Grade	*ITSI Performance Value*	*Priority*
Scheme Cost (C_{10})	High	0.099474	10
Acceptance (C_8)	Very High	0.095193	9
Safety (C_9)	High	0.090000	8
Annual DCIE for data center (C_6)	Medium	0.069028	7
Energy used per resource (C_5)	Low	0.060571	6
KG of CO_2 per IT resource (C_4)	Medium	0.041077	5
Road User Emissions (C_2)	Low	0.035508	4
Scheme lifecycle emissions (C_1)	Medium	0.033487	3
Roadside Energy Consumption (C_7)	Low/Medium	0.030000	2
Kg of CO2 off - IT certificates (C_3)	Very Low	0.002656	1
OVERALL PERFORMANCE	**Medium**	**0.556993**	

Table 15: Prioritised Sustainable Index Results

5.5 Discussion and Sensitivity Analysis

EnvFUSION is a performance framework designed to estimate performance against sustainability criteria despite uncertainties within the data set. Based upon the ITSI performance results in table 15, it is possible to produce a 'unified' analysis on which areas of the ITS scheme are performing acceptably and which areas can potentially be improved. From strongest to weakest (top to bottom in Table 14), the highest performing criterion (based upon the ITSI performance value) is 'scheme cost'.

This is due to not only the future target being met, but also the subjective performance grade being rated as 'high'. It is conjectured that this reflects the major reduction in scheme cost compared to traditional traffic flow improvement schemes such as road widening. The lowest performing criterion is that which reflects the extent to which the data center has established IT carbon reduction strategies. For this case study there are currently no carbon reduction strategies in place, despite ICT having a major influence on the emissions and energy of the Active Traffic Management scheme and therefore no targets.

With the correct knowledge and training, the energy efficiency of the data center may be improved through strategies such as following the guidelines of the EU Code of Conduct for Data Center Energy Efficiency etc. The criterion ‘Roadside-energy consumption’ also has a low rating due to the large increase in energy consumption compared with its pre-implementation state. A sensitivity analysis was carried out by varying the AHP criteria weights and the distance-to-target weights. Five scenarios were established (Table 16), prioritising the AHP weights based upon the embedded and operational emissions at the roadside with the remaining values distributed equally the energy consumption of the road C_7 the energy and emissions from the data center safety and acceptance (social sustainability pillar) and finally the economic sustainability pillar - scheme cost. Scenarios 6 through 10 (Table 17) illustrates the same sets of criteria (emissions, energy, ICT, social and economic) reaching their desired targets (Distance to target=1) with AHP values remaining unchanged.

Scenario/Priority	**AHP Criteria Value**
Scenario 1: Roadside Emissions	C1=0.4, C2=0.4, C3=0.025, C4=0.025, C5=0.025, C6=0.025, C7=0.025, C8=0.025, C9=0.025, C10=0.025
Scenario 2: Roadside Energy	C1=0.022, C2=0.8, C3=0.022, C4=0.022, C5=0.022, C6=0.022, C7=0.022, C8=0.022, C9=0.022, C10=0.022
Scenario 3: ICT Emissions	C1=0.033, C2=0.033, C3=0.2, C4=0.2, C5=0.2, C6=0.2, C7=0.033, C8=0.033, C9=0.033, C10=0.033
Scenario 4: Safety and Acceptance	C1=0.022, C2=0.022, C3=0.022, C4=0.022, C5=0.022, C6=0.022, C7=0.022, C8=0.4, C9=0.4, C10=0.022
Scenario 5: Economic	C1=0.022, C2=0.022, C3=0.022, C4=0.022, C5=0.022, C6=0.022, C7=0.022, C8=0.022, C9=0.022, C10=0.8
Scenario/Priority	**Distance-to-Target Criteria Value**
Scenario 6: Roadside Emissions	C1=1, C2=1, C3=0, C4=0, C5=0, C6=0, C7=0, C8=0, C9=0, C10=0
Scenario 7: Roadside Energy	C1=0, C2=1, C3=0, C4=0, C5=0, C6=0, C7=0, C8=0, C9=0, C10=0
Scenario 8: ICT Emissions	C1=0, C2=0, C3=1, C4=1, C5=1, C6=1, C7=0, C8=0, C9=0, C10=0
Scenario 9: Safety and Acceptance	C1=0, C2=0, C3=0, C4=0, C5=0, C6=0, C7=0, C8=1, C9=1.4, C10=0
Scenario 10: Economic	C1=0, C2=0, C3=0, C4=0, C5=0, C6=0, C7=0, C8=0, C9=0, C10=1

Table 16: AHP and DTT Sensitivity Analysis

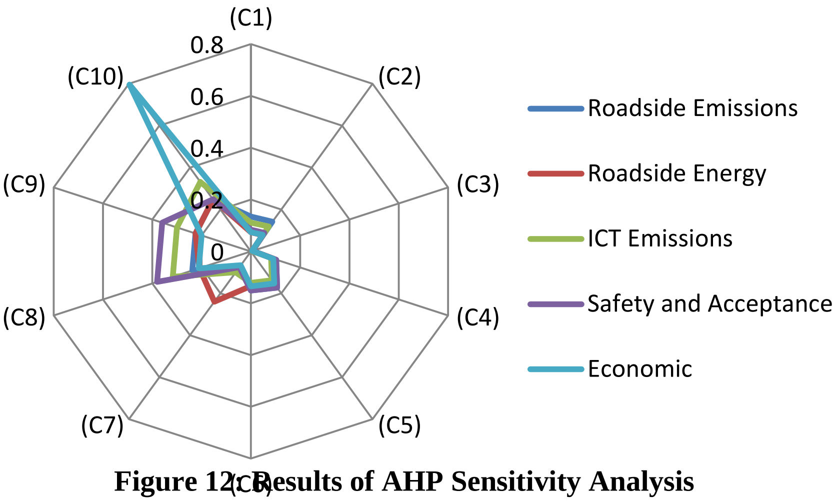

Figure 12: Results of AHP Sensitivity Analysis

Figures 12 and 13 illustrate the results of both the AHP and Distance-To-Target Sensitivity Analysis. The performance values of the criteria remain consistent with the variances in the AHP in each scenario. Of particular note is the lack of change at the top and bottom of the priority list.

This implies that scheme cost retains best performance while KG CO2 offset in the data center remains the top priority for improvement in sustainability. However, it appears that the distance-to-target method has considerable influence on the ITSI performance values, which indicates the model is sensitive to allocated targets. It is also argued that the basic probability assignments and distance-to-target values carry the most potential to change priorities. However, in the event that the BPA values are equal or "uncertain", the Analytical Hierarchy Process and the distance-to-target method actually assist in making a decision, demonstrating the robustness of EnvFUSION as a decision making tool.

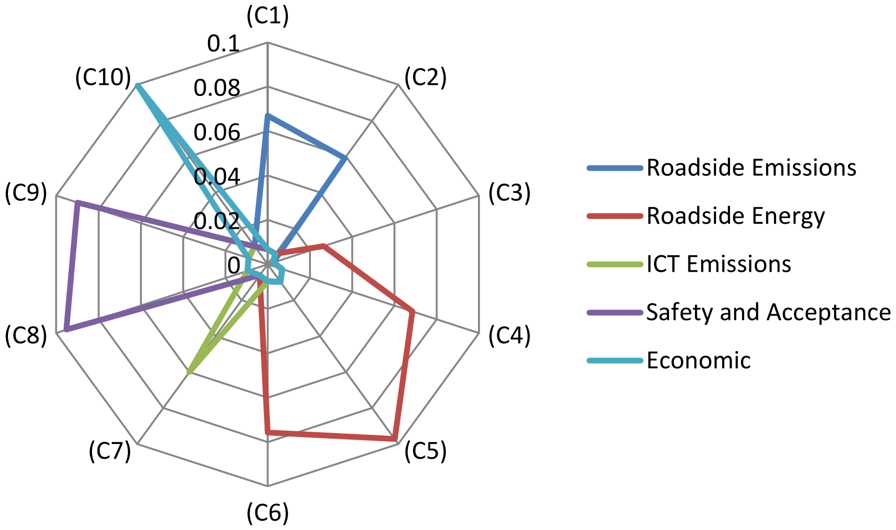

Figure 13: Results of Distance to Target Sensitivity Analysis

6 Conclusions

This paper begins with the premise that there is a gap in knowledge concerning the impacts of ITS schemes in terms of sustainability and difficulties in assessing these impacts due to the inherent nature of ITS i.e. as a system of systems. In reality, there are many relationships between the technology, the road users and emissions which add to the complexity of the system as a whole.

Moreover, recent increases in the implementation of technology indicate a need to estimate the level of carbon offset such technology can bring to the transport network. This research has aimed to address this gap by introducing a 'unified' sustainability framework that bridges existing standards and targets between ICT and transport impact assessments. It also takes inputs from various deficient or uncertain data sources in order to provide key performance indicators to estimate the emissions and socio-economic status of ATM schemes.

To summarise, the road-side infrastructure contributed around 9% (1.647 kilo-tonnes of CO2 equivalency) of lifecycle GWP with vehicle emissions remaining the dominant category. The emissions included the contribution of the ATM and improvements in vehicle technology. As a consequence of improved traffic flow, the scheme offsets the emissions from the original 2003 traffic flows by around 53 kilo-tonnes of CO_2 equivalency (4% reduction). The top four priorities of the ITSI index are the data center, roadside energy consumption, scheme lifecycle emissions and road user emissions. The main benefits of the EnvFUSION framework are as follows:

- the ability to integrate different transport and ICT variables alongside the infrastructure data in order to incorporate the operational (emissions and energy) consumption of the scheme in the overall indicator.
- the ability to make data that is individually incomplete an absolute whole using basic probability assignment and mass values
- the ability for international organisations and national governments to set targets using the distance-to-target method which will influence the priority of the ITS criteria under observation. This is particularly useful if the basic

probability assignments and analytical hierarchy process values are equal and a more refined decision has to be made.

The framework is intended to be complimentary to existing sectoral frameworks such as the UK Transport Carbon Model in its potential to reduce the ambiguity surrounding the embedded emissions of the transport infrastructure and thereby provides better support to long term decision making. Although EnvFUSION includes effects such as embedded and operational emissions from electricity generation, it is not an energy systems model nor is it solely a transport model, but acts as an interface between these and other factors to ensure these technologies remain sustainable over their entire lifecycle.

7 Further research

In order to increase the authenticity of the framework, increased complexity should be applied to more closely resemble the real-life decision making necessary to improve overall sustainability in ITS. For example, reliability issues within deficient data sources should be explored more thoroughly alongside the possibility of developing inter-scheme comparisons between two or more existing ITS services. The AHP approach would support this possibility by its use of decision alternatives.

While the case study described here is based on a scheme already in operation, the research can be extended to estimating potential energy and emissions reductions likely to arise from future technology advances. Future work will involve reconfiguring the LCA inventory from the current fixed data sets to dynamic marginalisation for certain forecasting periods using consequential cause and effect patterns up to 2050 (this being the timeline for most European and International governments’ ambitious 80% carbon reduction in transport). Finally, the work will consider embodied emissions of ICT, although this research area is relatively new and the supporting evidence sparse to date.

Acknowledgments

The authors would like to thank several contacts within the Highways Agency for their cooperation without whom this article would not be possible. Members of the supply procurement chain are also gratefully thanked for their assistance with data. All views expressed in the paper are entirely the authors' own and should not be taken to reflect the views of the Highways Agency or any cooperating parties.

References

AEA (2009). Updated Vehicle Emission Curves for Use in the National Transport Model. Report to the Department for Transport. AEA. Didcot, Department for Transport. Issue 2.

Ahlroth, S., Nilsson, M., Finnveden, G., et al. (2011). "Weighting and valuation in selected environmental systems analysis tools - suggestions for further developments." Journal of Cleaner Production 19(2-3): 145-156.

Arvanitoyannis, I. S. (2008). ISO 14040: Life Cycle Assessment (LCA) -- Principles and Guidelines. Waste Management for the Food Industries. S. A. Ioannis, Dr and Ph.D. Amsterdam, Academic Press: 97-132.

Awasthi, A. and Chauhan, S. S. (2011). "Using AHP and Dempster-Shafer theory for evaluating sustainable transport solutions." Environmental Modelling & Software 26(6): 787-796.

Basson, L. and Petrie, J. G. (2007). "An integrated approach for the consideration of uncertainty in decision making supported by Life Cycle Assessment." Environmental Modelling & Software 22(2): 167-176.

Benetto, E., Dujet, C. and Rousseaux, P. (2008). "Integrating fuzzy multicriteria analysis and uncertainty evaluation in life cycle assessment." Environmental Modelling & Software 23(12): 1461-1467.

Berl, A., Gelenbe, E., Di Girolamo, M., et al. (2010). "Energy-efficient cloud computing." The Computer Journal 53(7): 1045-1051.

Beynon, M. (2002). "DS/AHP method: A mathematical analysis, including an understanding of uncertainty." European Journal of Operational Research 140(1): 148-164.

Beynon, M., Curry, B. and Morgan, P. (2000). "The Dempster-Shafer theory of evidence: an alternative approach to multicriteria decision modelling." Omega 28(1): 37-50.

Bolte, F. (2006). Transport Policy Objectives: Traffic Management as Suitable Tool. Presentation to Planning for Congestion Management Scan Team. Federal Highway Research Institute (BASt). Bergisch-Gladbach, BASt.

Brander, M., Tipper, R., Hutchison, C., et al. (2009). "Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels." Technical paper TP-090403-A, Ecometrica Press, London, UK.

Brucker, K. D., Verbeke, A. and Macharis, C. (2004). "The Applicability of Multi-Criteria Analysis to the Evaluation of Intelligent Transport Systems (ITS)." Research in Transportation Economics 8: 151-179.

Chartered Institute for IT (2011). Certified Energy Efficient Datacentre Award (CEEDA): Recognising and rewarding best practice in datacentre energy efficiency. B. C. S. T. C. I. f. IT. Swindon.

Chen, I. C., Fukushima, Y., Kikuchi, Y., et al. (2012). "A graphical representation for consequential life cycle assessment of future technologies. Part 1: methodological framework." The International Journal of Life Cycle Assessment 17(2): 119-125.

Cherubini, F. and Strømman, A. H. (2011). "Life cycle assessment of bioenergy systems: State of the art and future challenges." Bioresource Technology 102(2): 437-451.

Christiansen, K. and SETAC-Europe (1997). Simplifying LCA: Just a Cut?: Final Report from the SETAC-Europe LCA Screening and Streamlining Working Group, SETAC-Europe.

Cooper, J., Noon, M. and Kahn, E. (2012). "Parameterization in Life Cycle Assessment inventory data: review of current use and the representation of uncertainty." The International Journal of Life Cycle Assessment: 1-7.

Dao, V., Langella, I. and Carbo, J. (2011). "From green to sustainability: Information Technology and an integrated sustainability framework." The Journal of Strategic Information Systems 20(1): 63-79.

Deakin, E., Frick, K. and Skabardonis, A. (2009). "Intelligent Transport Systems." ACCESS 34(Spring 2009).

Dempster, A. (2008). "A generalization of Bayesian inference." Classic Works of the Dempster-Shafer Theory of Belief Functions: 73-104.

Dempster, A. P. (1968). "A generalization of Bayesian inference." Journal of the Royal Statistical Society. Series B (Methodological) 30(2): 205-247.

Department for Transport (2008). Roads - Delivering Choice and Reliability. DfT. London, Department for Transport.

European Commission JRC (2010a). ILCD Handbook: International Reference Lifecycle Data System - General guide for Lifecycle Assessment - Detailed guidance. Luxembourg, Publications Office of the European Union.

European Commission JRC (2010b). International Reference Life Cycle Data System (ILCD) Handbook - Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. Luxembourg, Publications Office of the European Union, 2010.

Finnegan, S., Tickell, R. and Booth, K. (2004). "A Life Cycle Assessment (LCA) of Alternative Fuels in Transport Operation." Department of Civil Engineering, The University of Liverpool.

Finnveden, G., Hauschild, M. Z., Ekvall, T., et al. (2009). "Recent developments in Life Cycle Assessment." Journal of Environmental Management 91(1): 1-21.

Frischknecht, R., Jungbluth, N., Althaus, H. J., et al. (2005). "The ecoinvent database: Overview and methodological framework (7 pp)." The International Journal of Life Cycle Assessment 10(1): 3-9.

Frischknecht, R. and Rebitzer, G. (2005). "The ecoinvent database system: a comprehensive web-based LCA database." Journal of Cleaner Production 13(13-14): 1337-1343.

Goedkoop, M., Schryver D, A., Oele, M., et al. (2010). SimaPro: Introduction to LCA. P. Consultants.

Guinée, J., Udo de Haes, H. and Huppes, G. (1993a). "Quantitative life cycle assessment of products:: 1: Goal definition and inventory." Journal of Cleaner Production 1(1): 3-13.

Guinée, J. B., Heijungs, R., Udo de Haes, H. A., et al. (1993b). "Quantitative life cycle assessment of products : 2. Classification, valuation and improvement analysis." Journal of Cleaner Production 1(2): 81-91.

Hermann, B. G., Kroeze, C. and Jawjit, W. (2007). "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators." Journal of Cleaner Production 15(18): 1787-1796.

Higgs, T., Cullen, M., Yao, M., et al. (2010). Review of LCA methods for ICT products and the impact of high purity and high cost materials. Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on.

Highways Agency (2009). Managed Motorways Implementation Guidance: Hard Shoulder Running. Intermin Advice Note 111/09. H. Agency**:** 97-99.

Hilty, L. M., Arnfalk, P., Erdmann, L., et al. (2006). "The relevance of information and communication technologies for environmental sustainability – A prospective simulation study." Environmental Modelling & Software 21(11): 1618-1629.

Hunt, R. G., Boguski, T. K., Weitz, K., et al. (1998). "Case studies examining LCA streamlining techniques." The International Journal of Life Cycle Assessment 3(1): 36-42.

International Standards Organisation (2006). BS EN ISO 14040: Environmental Management - Lifecycle Assessment - Principles and Framework. B. S. Institute. London, BSI.

IPCC, W. (2001). "Climate change 2001: the Scientific basis." Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, Cambridge, 2001): 881.

Ju, Y. and Wang, A. (2012). "Emergency alternative evaluation under group decision makers: A method of incorporating DS/AHP with extended TOPSIS." Expert Systems with Applications 39(1): 1315-1323.

Kolosz, B., W., Grant-Muller, S. and Djemame, K. (2012). Integrated Strategic Performance Toolkit for Cooperative Scheme Comparisons in Inter-Urban Intelligent Transport Services. Proceedings of the 19th ITS World Congress, Vienna, Austria, ITS Austria.

Leduc, G., Mongelli, I., Uihlein, A., et al. (2010). "How can our cars become less polluting? An assessment of the environmental improvement potential of cars." Transport Policy 17(6): 409-419.

Lund, H., Mathiesen, B., Christensen, P., et al. (2010). "Energy system analysis of marginal electricity supply in consequential LCA." The International Journal of Life Cycle Assessment 15(3): 260-271.

Malça, J. and Freire, F. (2011). "Life-cycle studies of biodiesel in Europe: A review addressing the variability of results and modeling issues." Renewable and Sustainable Energy Reviews 15(1): 338-351.

Mathiesen, B. V., Münster, M. and Fruergaard, T. (2009). "Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments." Journal of Cleaner Production 17(15): 1331-1338.

Matsumiya, T. (2011). "Steelmaking technology for a sustainable society." Calphad 35(4): 627-635.

Matthews, W. A., Wood, S. and Connor, B. (2007). "Sustainability and greenhouse gases: What are the issues for New Zealand?" Environmental Modelling & Software 22(3): 288-296.

Mirshahi, M., Obenberger, J., Fuhs, C., A, et al. (2007). Active Traffic Management: The Next Step in Congestion Management. Active Traffic Management. U. D. o. T. F. H. Administration. Washington, US Department of Transportation Federal Highway Administration**:** 84.

NAEI (2012). Basic Fleet Projections - Proportion of VKM by Vehicle Type, Road Type and DA Regions. NAEI. NAEI. London.

Ogawa, M. J., Arlow, A. J., Meekums, R. J., et al. (2010). M42 Active Traffic Management monitoring and evaluation: Results from Hard Shoulder Running up to 60 mph. Road Transport Information and Control Conference and the ITS United Kingdom Members' Conference (RTIC 2010) - Better transport through technology, IET.

Ossés de Eicker, M., Hischier, R., Kulay, L. A., et al. (2010). "The applicability of non-local LCI data for LCA." Environmental Impact Assessment Review 30(3): 192-199.

Patey, I., Conquest, J. and Holt, A. (2008). "Assessing carbon balance of intelligent transport schemes." Proceedings of the ICE-Engineering Sustainability 161(3): 181-184.

Pieragostini, C., Mussati, M. C. and Aguirre, P. (2012). "On process optimization considering LCA methodology." Journal of Environmental Management 96(1): 43-54.

Psaraki, V., Pagoni, I. and Schafer, A. (2012). "Techno-economic assessment of the potential of intelligent transport systems to reduce CO2 emissions." Intelligent Transport Systems, IET 6(4): 355-363.

Rajagopal, D., Hochman, G. and Zilberman, D. (2011). "Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies." Energy Policy 39(1): 228-233.

Rebitzer, G., Ekvall, T., Frischknecht, R., et al. (2004). "Life cycle assessment:: Part 1: Framework, goal and scope definition, inventory analysis, and applications." Environment International 30(5): 701-720.

Saaty, T. L. (1980). The Analytic Hierarchy Process. New York.

Saaty, T. L. (1990). "How to make a decision: The analytic hierarchy process." European Journal of Operational Research 48(1): 9-26.

Sambasivan, M. and Fei, N. Y. (2008). "Evaluation of critical success factors of implementation of ISO 14001 using analytic hierarchy process (AHP): a case study from Malaysia." Journal of Cleaner Production 16(13): 1424-1433.

Sandén, B. A. and Karlström, M. (2007). "Positive and negative feedback in consequential life-cycle assessment." Journal of Cleaner Production 15(15): 1469-1481.

Shafer, G. (1976). A mathematical theory of evidence, Princeton university press Princeton, NJ.

Spielmann, M. and Scholz, R. (2005). "Lifecycle inventories of transport services." International Journal of LCA 10(1): 85–94.

Stansberry, M. and Kudritzki, J. (2012). 2012 Data Center Industry Survey. Data Center Industry Survey. U. Institute. Bend, Oregon, Uptime Institute.

Stobbe, L., Nissen, N. F., Schischke, K., et al. (2009). Methodology and utilization of simplified eco-assessments for policy making. Sustainable Systems and Technology, 2009. ISSST '09. IEEE International Symposium on.

Sultan, B. (2009). ATM Monitoring and Evaluation: 4 Lane Variable Mandatory Speed Limits - 12 Month Report. ATM Monitoring and Evaluation. H. Agency. Bristol, Highways Agency. V3.

Weidema, B. P. and Wesnæs, M. S. (1996). "Data quality management for life cycle inventories--an example of using data quality indicators." Journal of Cleaner Production 4(3-4): 167-174.

Weiss, M., Patel, M., Heilmeier, H., et al. (2007). "Applying distance-to-target weighing methodology to evaluate the environmental performance of bio-based energy, fuels, and materials." Resources, Conservation and Recycling 50(3): 260-281.

WSDoT (2012). "I-5 - Active Traffic Management - Complete August 2010." Agency Projects. Retrieved November, 2012.

Yao, R., Yang, Y. and Li, B. (2012). "A holistic method to assess building energy efficiency combining D-S theory and the evidential reasoning approach." Energy Policy 45(0): 277-285.

Yellishetty, M., Mudd, G. M. and Ranjith, P. G. (2011a). "The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue?" Journal of Cleaner Production 19(1): 78-90.

Yellishetty, M., Mudd, G. M., Ranjith, P. G., et al. (2011b). "Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects." Environmental Science & Policy 14(6): 650-663.

Žilina, U. (2009). "Present and Future Challenges of ICT for Intelligent Transportation Technologies and Services." 2009 1ST International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology. 1,2: 112-115.

---

[i] Refer to Saaty (1990) for a full overview on the AHP method.

[ii] We refer to lifespan as the duration of operational activity before the gantry requires replacing and should not be confused with lifecycle assessment. This is to avoid the possibility of improved or alternative technologies disrupting the emissions results which leads to significant levels of uncertainty. See Further Research.

[iii] Note that the bpa values have been altered in order to maintain anonymity with the source material

[iv] Refer to Shafer (1973) and Beynon et al (2000)