Assessing the Sustainability Performance of Inter-Urban Intelligent Transport

by

Ben William Kolosz

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The candidate confirms that the work submitted is his own. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Out of the chapters that make up the content of the thesis, the following contains material that has been published by journals and conference proceedings: Chapter 2 - Defining sustainability performance for Intelligent Transport (**1,2,3**); Chapter 4 - A review of sustainability assessment approaches for inter-urban Intelligent Transport (**1,2**); Chapter 5 - Development of the study and data collection strategy (**1,2**); Chapter 6 - Evaluation of current inter-urban ITS systems: Active Traffic Management (**1**); Chapter 7 - Evaluation of future inter-urban ITS systems (**2**); Chapter 8 - Modelling ITS socio-technical parameters for inter-scheme comparisons (**3**).

*(1) **Kolosz, B, W**., Grant-Muller, S, M and Djemame, K.,(2013) (2013). "Modelling uncertainty in the sustainability of Intelligent Transport Systems for highways using probabilistic data fusion." Environmental Modelling & Software 49: 78-97. DOI: http://dx.doi.org/10.1016/j.envsoft.2013.07.011*

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*(3) **Kolosz, B, W**., Grant-Muller, S, M 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, 22/26 October, 2012. Paper Number: EU-00193*

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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. This thesis 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 three types of Intelligent Transport System. Active Traffic Management, Intelligent Speed Adaptation and the Automated Highway System are a collection of systems designed to transform the road network into a highly efficient and congestion free transport solution and all possess varying levels of uncertainty in terms of sustainability performance.

The performance criteria form part of a new framework methodology 'EnvFUSION' (Environmental Fusion for ITS) outlined here. An attributional LCA and c-LCA (consequential lifecycle assessment) are both undertaken which forms part of a data fusion process using data from various sources. The models forecast improvements for the three ITS technologies in-line with social acceptability, economic profitability and major carbon reduction scenarios up to 2050 on one of the UK's most congested highways. Analytical Hierarchy Process and Dempster-Shafer theory are used to weight criteria which form part of an Intelligent Transport Sustainability Index. Overall performance is then synthesized. Results indicate that there will be a substantial increase in socio-economic and emissions benefits, provided that the policies are in place and targets are reached which would otherwise delay their realisation. To conclude, an integrated strategic performance management framework is proposed which performs socio-technical comparisons of four key performance areas between ITS schemes in order to identify energy and emission hotspots.

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Glossary of Acronyms

Acronym	Description
AADF - Annual Average Daily Traffic Flows	Annual average daily traffic, abbreviated AADF, is a measure used primarily in transportation planning and transportation engineering. It is the total volume of vehicle traffic of a highway or road for a year divided by 365 days. AADT is a useful and simple measurement of how busy the road is. It is sometimes incorrectly reported as "average annual daily traffic".
ADS - Advanced Direction Sign	An ADS generally has blue, green or white as its background colour to indicate the status of road (motorway, primary or non-primary) on which it is placed. Except on the main carriageway of a motorway, coloured panels are used to indicate routes from the junction being signed that have a different status. A DS should always be a single colour indicating the status of the road to be joined, although there are a few rare exceptions to this rule.
AHP - Analytical Hierarchy Process	The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions. Based on mathematics and psychology, it was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then.
AHS - Automated Highway System	AHS provides services and support infrastructure required for vehicles to drive autonomously while the driver is effectivley disconneted from operations. Platooning for example can enhance efficiency by allowing vehicles to drive in close proximity to form autonomous road trains.
AMI - Advanced Motorway Indicator	The AMI is an advanced motorway indicator designed to guide traffic and enforce speed limits on ATM schemes. The AMI provides Optical Feedback providing actual light-emitted detection to enable legal enforcement. Its features include a Flexible multicolour display; Red, Amber, Green, White. Controlled motorway applications include variable speed limit signs, lane control indicators, dynamic lane control units, lane control signals and controlled motorway indicators.
Analytical Network Process	The analytic network process (ANP) is a more general form of the analytic hierarchy process (AHP) used in multi-criteria decision analysis.AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network. Both then use a system of pairwise comparisons to measure the weights of the components of the structure, and finally to rank the alternatives in the decision.
ATM - Active Traffic Management	Active Traffic Management consists of the dynamic control and marshalling of the transport network under severe congestion. The components of ATM include physical infrastructure such as overhead gantries, surveillance and sensor networks.
BPA - Basic Probability Assignment	Dempster–Shafer theory allows the construction of belief functions from (precise) basic probability assignments. In the absence of empirical data, experts in related fields provide necessary information (bpa). However how to obtain BPA is still an open issue with the majority of data collection focusing on best guess or ad-hoc approaches.

Acronym	Description
BPI - Bayesian Probability Inference	Bayesian probability is one of the different interpretations of the concept of probability and belongs to the category of evidential probabilities. The Bayesian interpretation of probability can be seen as an extension of propositional logic that enables reasoning with propositions whose truth or falsity is uncertain.
CASS - Collision Avoidance Support Systems	CASS are designed to alert and protect drivers from oncoming collisions with enough time to make a suitable evasive manoeuvre or take complete control and make the manoeuvre automatically. It is considered to be one of the main researching lines in Driver Assistance Systems (DAS). Many researchers refer to this service when designing communication architectures for automated and supportive driving systems.
CBA - Cost Benefit Analysis	Cost-benefit analysis (CBA), sometimes called benefit–cost analysis (BCA), is a systematic process for calculating and comparing benefits and costs of a project, decision or government policy (hereafter, "project"). CBA has two purposes: To determine if it is a sound investment/decision (justification/feasibility) and to provide a basis for comparing projects. It involves comparing the total expected cost of each option against the total expected benefits, to see whether the benefits outweigh the costs, and by how much.
CEA - Cost Effectiveness Analysis	Cost-effectiveness analysis (CEA) is a form of economic analysis that compares the relative costs and outcomes (effects) of two or more courses of action. Cost-effectiveness analysis is distinct from cost-benefit analysis, which assigns a monetary value to the measure of effect
CEC - Combined Equipment Cabinet	A cabinet which house various road-side traffic infrastructure. It is currently being utilised on the UK ATM schemes.
CLCA - Consequential Lifecycle Assessment	The CLCA is a sophisticated modelling technique that provides a way to assess the environmental consequences of an action/decision by including market mechanisms into the analysis whether in the short-term or long-term. The development of the method and its methodology is currently ongoing.
CSI - Continual Service Improvement	Continual Service Improvement is the continual alignment and adjustment of IT Services to meet the changing business needs by identifying and implementing improvements to IT Services that support Business Processes. It is part of ITIL's service improvement lifecycle for the delivery of IT Services.
CUE - Carbon Usage Effectiveness	Carbon usage effectiveness (CUE) is a metric for measuring the carbon gas a data center emits on a daily basis. The metric was developed by the non-profit consortium, The Green Grid.
CVIS - Cooperative Vehicle Infrastructure Systems	An ongoing project that has been initiated by the European Union and is the counterpart to Americas VII (Vehicle Infrastructure Integration) solution. CVIS is used to represent all wireless communications platforms and infrastructure within ITS. Over 60 European companies have provided input. The Highways Agency is currently involved with this project.
DAS - Driver Assistance Systems	DAS is a term used to describe applications which will 'assist' the driver from information and safety warnings to providing partial control of the vehicle when approaching a junction or roundabout. When designed with a suitable HMI (Human-Machine Interface) Technologies in development under this field include ISA (Intelligent Speed Adaptation), ACC (Adaptive Cruise Control) and CAR2CAR communication.

Acronym	Description
DECC - Department of Energy and Climate Change	The DECC was created in October 2008 in order to group together energy policy (which was originally with BERR and is now BIS – Department of Business Innovation and Skills) and climate mitigation policy (previously Defra – the department for environment, food and rural affairs. Climate change is a serious issue and the department has been created in order to help reduce this threat via creating and maintaining appropriate policies.
DCIE - Data Center Infrastructure Efficiency	Data center infrastructure efficiency (DCIE), is a performance improvement metric used to calculate the energy efficiency of a data center. DCIE is the percentage value derived, by dividing information technology equipment power by total facility power
DfT - Department for Transport	The department for transport is a government department involved with the entire road network in England and road matters in Scotland, Wales and northern island. The Secretary of State for Transport runs the department. Their aim is to deliver a transport system that works for everyone via balancing the requirements of the environment, economy and society.
DNO - Distribution Network Operator	Distribution network operators (DNOs) are companies licensed to distribute electricity in Great Britain by the Office of Gas and Electricity Markets. There are fourteen licensed areas, based on the former Area Electricity Board boundaries, where the DNO distributes electricity from the transmission grid to homes and businesses. They are also responsible for allocating the core MPAN in their respective areas.
DSRC - Dedicated Short Range Communications	DSRC is a selection of one-way, two-way short to medium wireless communication channels that are designed specifically for vehicular use. Protocols and standards are designed specifically to use the specific channels.
DST - Dempster-Shafer Theory	The Dempster–Shafer theory (DST) is a mathematical theory of evidence. It allows one 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. The theory was first developed by Arthur P. Dempster and Glenn Shafer.
DTT - Distance to Target method	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.
EC - European Commission	The European Commission (EC) is the executive body of the European Union responsible for proposing legislation, implementing decisions, upholding the Union's treaties and day-to-day running of the EU
EF - Ecological Footprint	The ecological footprint is a measure of human demand on the Earth's ecosystems. It is a standardized measure of demand for natural capital that may be contrasted with the planet's ecological capacity to regenerate. It represents the amount of biologically productive land and sea area necessary to supply the resources a human population consumes, and to assimilate associated waste.
EIA - Environmental Impact Assessment	An environmental impact assessment (EIA) is an assessment of the possible impacts that a proposed project may have on the environment, consisting of the environmental, social and economic aspects. The purpose of the assessment is to ensure that decision makers consider the environmental impacts when deciding whether or not to proceed with a project.

Acronym	Description
ELD - Ecoinvent Lognormal Distribution	In probability theory, a log-normal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. It is used in the Ecoinvent database through Monte Carlo analysis to estimate total uncertainty of environmental burden from a variety of selected data quality criteria unique to Ecoinvent.
EMS - Environmental Management System	Environmental management system (EMS) refers to the management of an organization's environmental programs in a comprehensive, systematic, planned and documented manner. It includes the organizational structure, planning and resources for developing, implementing and maintaining policy for environmental protection.
EnvFUSION - Environmental Fusion for ITS	EnvFUSION is the proposed sustainability performance framework that has been developed in this thesis in order to reduce ambiguity surrounding current ITS appraisal.
EPI - Environmental Performance Indicator	The Environmental Performance Index (EPI) is a method of quantifying and numerically benchmarking the environmental performance of a state's policies. This index was developed from the Pilot Environmental Performance Index, first published in 2002, and designed to supplement the environmental targets set forth in the United Nations Millennium Development Goals.
EPS - Environmental Priority Strategy	The Environmental Priority System (EPS) is a method of evaluation of LCA , which for the first time by Bengt Steen (IVL - Swedish Environmental Research Institute) and Sven-Olof Ryding (Swedish Industry Association) was published in 1990.
ERA - Environmental Risk Assessment	EIA is required for projects that carry a greater environmental burden while ERA is often voluntarily carried out via agencies to assist in their decision making ERA's most common method known as stress response analysis can be used to evaluate the potential environmental impacts caused by the projects (for example the construction of a dam on a river). Therefore ERA can be considered as a complement to EIA.
ERTICO - European Road Transport Telematics Implementation Coordination	ERTICO is the official European body for ITS. It is funded by the European Commission. Its current mission is to fund research and develop standards which will help the successful implementation of ITS services. ERTICO brings together public authorities, industry players, infrastructure operators, users, national ITS associations and other organizations within Europe and works closely with ITS America and ITS Japan.
ESAT - Environmental System Analysis Tool	ESATs are designed to assess environmental impacts of the systems studied. One of their central tasks is to evaluate environmental impacts. These take many different forms and therefore it can be difficult to comprehend and draw conclusions from a long list of environmental impact factors and their effects.
ETA - Estimated Time of Arrival	The estimated time of arrival or ETA (Sometimes called ETOA) is a measure of when a ship, vehicle, aircraft, cargo, emergency service or computer file is expected to arrive at a certain place. One of the more common uses is in public transportation where the movements of trains, buses, airplanes and the like can be used to generate estimated times of arrival depending on either a static timetable or through measurements on traffic intensity

Acronym	Description
EU ETS - Emissions Trading Scheme	Emissions trading or cap and trade is a market-based approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants.
GAF - Geographical Adaptive Fidelity	A form of network management protocol which allows for a 'green' energy saving data transmission for vehicular networks.
GHG - Greenhouse Gas	A greenhouse gas (sometimes abbreviated GHG) is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect
GPS - Global Positioning System	The Global Positioning System (GPS) is a space-based satellite navigation system that provides location and time information in all weather conditions, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. The system provides critical capabilities to military, civil and commercial users around the world. It is maintained by the United States government and is freely accessible to anyone with a GPS receiver.
GDP - Gross Domestic Product	Gross domestic product (GDP) is the market value of all officially recognized final goods and services produced within a country in a given period of time. GDP per capita is often considered an indicator of a country's standard of living.
GWP - Global Warming Potential	Global-warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1).
HA - Highways Agency	An executive agency which its parent organisation is the department for transport (DfT). Its formation was in 1994 and its mission is the operation of the strategic road network in England, including all motorways and major 'A' roads. It caters for 34% of all road travel and 67% of freight travel. In addition it also liaisons with other organisations in Europe and provides information services to drivers.
HADECS - Highways Agency Digital Enforcement Camera System	HADECS is the Highways Agency Digital Enforcement Camera System which has been designed for use on motorway gantries. It has been developed with the HA to support the application of mandatory variable speed limits on selected motorways. The system automatically enforces the variable speed limits indicated by the Advanced Motorway Indicators (AMI's) when displaying the 'Red Ring' variable speed limits.
HGV - Heavy Goods Vehicle	A large goods vehicle (also heavy goods vehicle, medium goods vehicle, LGV and HGV), is the European Union term for any truck with a gross combination mass (GCM) of over 3,500 kilograms (7,716).[Sub-category N2 is used for vehicles between 3,500 kilograms (7,716 lb) and 12,000 kilograms (26,455 lb) and N3 for all goods vehicles over 12,000 kilograms (26,455 lb) as defined in Directive 2001/116/EC.
HOV - High Occupancy Vehicle Lane	A high-occupancy vehicle lane (also known as a HOV lane, carpool lane, diamond lane, and transit lane or T2 or T3 lanes in Australia and New Zealand) is a restricted traffic lane reserved at peak travel times or longer for exclusive use of vehicles with a driver and one or more passengers, including carpools, vanpools and transit buses.

Acronym	Description
ICT - Information and Communication Technologies	Information communication technology describes the technical field of computing, scientific and technical research for information management. In relation to ITS, an ICT layer provides the capability of ICT to enable ITS service provision such as technical communication systems and data networks.
IEEE - Institute of Electrical and Electronics Engineers	The IEEE is an Engineering based institute which offers membership at various levels. It is also a research body that produces regular articles from fellow researchers internally as well as from other institutions (academic and industrial).
IPCC - Intergovernmental Panel on Climate Change	The Intergovernmental Panel on Climate Change (IPCC) is a scientific intergovernmental body, set up at the request of member governments. It was first established in 1988 by two United Nations organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and later endorsed by the United Nations General Assembly through Resolution 43/53.
ISA - Intelligent Speed Adaptation	Intelligent Speed Adaptation (ISA), also known as Intelligent Speed Assistance, Speed Alerting, and Intelligent Speed Authority, is any system that constantly monitors vehicle speed and the local speed limit on a road and implements an action when the vehicle is detected to be exceeding the speed limit. This can be done through an advisory system, where the driver is warned, or through an intervention system where the driving systems of the vehicle are controlled automatically to reduce the vehicle's speed.
ISO	The International Organization for Standardization (known as ISO, is an international standard-setting body composed of representatives from various national standards organizations.
ITIL - Information Technology Infrastructure Library	The Information Technology Infrastructure Library (ITIL) is a set of concepts and practices for Information Technology Services Management (ITSM), Information Technology (IT) development and IT operations. ITIL gives detailed descriptions of a number of important IT practices and provides comprehensive checklists, tasks and procedures that any IT organization can tailor to its needs. ITIL is published in a series of books, each of which covers an IT management topic
ITS - Intelligent Transport Systems	An amalgamation of transport and technical ICT cooperation. An ITS service differs from conventional transport because of its dynamic nature, its ability to improve efficiency and solve complex tasks. The general outcome is either improved navigation, safety or security and just recently its proposed ability to aid the reduction in carbon which directly impacts climate change.
ITSM - Information Technology Service Management	IT service management (ITSM or IT services) is a discipline for managing information technology (IT) systems, philosophically centered on the *customer's perspective of IT's contribution to the business.* ITSM stands in deliberate contrast to technology-centered approaches to IT management and business interaction.
ITU - International Telecommunication Union	International Telecommunication Union is responsible for developing international telecommunications standards. However, their work goes much further than basic communication technology and they now develop technical standards for ITS Research and deployment. ITU-T is the formal standardisation department that focuses on all ITS aspects.

Acronym	Description
ITSI - Intelligent Transport Sustainability Index	An index that is designed to assess current and future sustainability performance through providing a ranking based on probability assignments, prioritised criteria and regional and national targets. The index is part of the EnvFUSION framework developed within this thesis.
IVC - Inter-Vehicle Communications	Inter-vehicle communications describes a communications framework which is designed to enable information exchange between vehicles. The main objective of IVC is to enable the vehicle to receive and distribute information relative in time and space about the environment in order for the driver to avoid major traffic incidents. With the right amount of information it is proposed that higher levels of safety will be achieved.
LCA - Lifecycle Analysis	Life-cycle assessment (LCA, also known as life-cycle analysis, ecobalance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).
LCCA - Lifecycle Cost Analysis	Life cycle cost analysis (LCCA) is a tool to determine the most cost-effective option among different competing alternatives to do a project, when each is equally appropriate to be implemented on technical grounds. For example, for a highway pavement, apart from the initial construction cost, LCCA takes into account all the user costs, (e.g., reduced capacity at work zones), and agency costs related to future activities, including future periodic maintenance and rehabilitation. All the costs are usually discounted and totaled to a present day value known as net present value (NPV). This example can be generalized on any type of material, product, or system.
LCI - Lifecycle Inventory	Life Cycle Inventory (LCI) analysis involves creating an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. To develop the inventory, a flow model of the technical system is constructed using data on inputs and outputs.
LCIA - Lifecycle Impact Assessment	Inventory analysis is followed by impact assessment. This phase of LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results.
LGV - Light Goods Vehicle	A light commercial vehicles is the official term used within the European Union for a commercial carrier vehicle with a gross vehicle weight of not more than 3.5 tonnes; the term light goods vehicle (LGV) may also be used by member countries (UK etc) which can be confused with Large goods vehicle (also 'LGV') which is the official EU term for a vehicle with a gross vehicle weight of over 3.5 tonnes.
MCA - Multi-Criteria Analysis	Multi criteria analysis is a widely regarded transport planning tool which takes many factors which have "weights" attached. All of the factors and weights are summarised in a performance matrix which can give a clear indication of selecting from a number of decisions based on personal preference.
MIDAS - **Motorway Incident Detection and Automatic Signalling**	Motorway Incident Detection and Automatic Signalling, usually abbreviated to MIDAS, is a distributed network of traffic sensors, mainly inductive loops, (trialling at the moment radar technology by wavetronix) which are designed to alert the local RCC (Regional Control Centre) to traffic flow and average speeds and in ATM (Active Traffic Management) zones, set variable message signs, advisory speed limits along with mandatory speed limits in ATM sections with little human intervention.

Acronym	Description
MM-HSR - Managed Motorways-Hard Shoulder Running	MM-HSR is a set of implementation guidelines for the successful installation and management of a fully loaded motorway utilising the hard shoulder running mode. It is the UK equivalent of the temporary shoulder running ATM technology.
MS3 - Message Sign Mark 3	Version 3 of a motorway message sign. The MS/ MS3 Series consists of three models which conforms to European specification EN12966. It offers 2 and 3 lines of text. The 400mm character signs incorporate a graphics area capable of displaying symbols and legends and flexible messaging capability. Other features include an alphanumeric, legend and symbol display, Character size, configuration and mounting options and RIGEL LED technology. Applications include variable speed limit signs, lane control indicators, lane control and controlled motorway indicators.
MS4 - Message Sign Mark 4	Version 4 of a motorway message sign which conforms to European specification EN12966. The MS4 is designed to meet the changing needs of traffic authorities and improve the quality of information available to motorists. The MS4 Series offers a full graphics area with a matrix of LED in two colours. This makes it capable of displaying an almost infinite range of pictograms and legends. Features include a flexible two colour display - red, amber, green or white. A full matrix display is available in a number of different size, includes RIGEL LED technology, cost effective, lighter in weight. The MS4 is also fully programmable to include text displays.
NAEI - National Atmospheric Emissions Inventory	The National Atmospheric Emissions Inventory (NAEI) is funded by the Department of Energy and Climate Change (DECC), Department for Environment, Food and Rural Affairs (Defra), the Scottish Government, the Welsh Government, and the Department of Environment, Northern Ireland. The NAEI compiles estimates of emissions to the atmosphere from UK sources such as power stations, traffic, household heating, agriculture and industrial processes.
NPV - Net Present Value	In finance, the net present value (NPV) or net present worth (NPW) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows of the same entity.
NRTS - National Roads Telecommunication Services	The NRTS project provides a service that carries data from roadside devices to traffic control offices. Through the new transmission network services that it provides, NRTS is accelerating the Agency's move towards digital communications. Digital technology is inherently more reliable, more manageable and more flexible than previous generations of communications technology. The NRTS contract was awarded in September 2005 to the GeneSYS consortium.
NTM - National Transport Model (UK)	The UK National Transport Model (NTM) provides a systematic means of comparing the national consequences of alternative national transport policies or widely-applied local transport policies, against a range of background scenarios which take into account the major factors affecting future patterns of travel.
PReVENT - Preventative and Safety Applications	PReVENT is a European based project which is funded by the European commission which its aim is to improve road safety via designing and implementing safety-based applications and technologies. This is accomplished via in-vehicle systems which detect and grade various levels of danger based upon the drivers current status.

Acronym	Description
PUE - Power Usage Effectiveness	Power usage effectiveness (PUE) is a measure of how efficiently a computer data center uses energy; specifically, how much energy is used by the computing equipment (in contrast to cooling and other overhead). PUE is the ratio of total amount of energy used by a computer data center facility to the energy delivered to computing equipment.
PTZ-CCTV - Pan, Tilt, Zoom - Close Circuit Television	A flexible multiple oriented security camera.
RSD - Remote Sensing Detector	A vehicle emission remote sensing detector (RSD) technique. RSD techniques were originally developed in the USA to measure the emissions of poorly maintained vehicles with a high emissions factor.
RSU - Roadside Unit	A road-side Unit is a form of physical infrastructure which can be used to display messages or send and receive traffic related data.
SEA - Strategic Environmental Assessment	Strategic environmental assessment (SEA) is a systematic decision support process, aiming to ensure that environmental and possibly other sustainability aspects are considered effectively in policy, plan and programme making.
SEEA - System of Environmental-Economic Accounting	The SEEA is a system for organizing statistical data for the derivation of coherent indicators and descriptive statistics to monitor the interactions between the economy and the environment and the state of the environment to better inform decision-making. The SEEA does not propose any single headline indicator. Rather it is a multi-purpose system that generates a wide range of statistics and indicators with many different potential analytical applications.
SOGE - Sustainable Operations on the Government Estate	SOGE is a department within the government that is dedicated to enforce and maintain sustainability within the government estate.
STI - Service Type Instance	A service type instance is a type of service dedicated to a specific role in a certain location. STI's are relevant to the National Road Telecommunication Framework.
SEM - Structural Equation Model	Structural equation modelling (SEM) is a statistical technique for testing and estimating causal relations using a combination of statistical data and qualitative causal assumptions.
SDM - Systems Dynamics Modelling	System dynamics is an approach to understanding the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire system. What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity.
TCC - Traffic Control Centre	A traffic control centre is designed to monitor the network within its appropriate boundary region and take action through implementing procedures when appropriate to improve safety and efficiency using road-side technology.
TEE - Transport Energy Environment	TEE models aim to combine the cause and effect feedback between transport, the energy and the environment and relate the results within the context of specific policy scenarios.
UKTCM - UK Transport Carbon Model	The UK Transport Carbon Model is a TEE research project that has been developed to estimate the impact of transport upon the environment via the use of specific national policy scenarios.

Acronym	Description
V2C - Vehicle to (Traffic) Control Centre	A form of communication within the field of CVIS. The vehicle will communicate to the TCC which will send information including; the current position, speed and other variables associated with the management of the traffic network.
V2I - Vehicle-to-Infrastructure	A form of communication in the field of CVIS and a derivative of V2C. The vehicle will communicate to the Infrastructure displaying various information which is required to update the traffic network in real-time. Information includes the relaying of current position, speed etc.
V2V - Vehicle-to-Vehicle	A form of communication within the field of CVIS. The vehicle sends data to other vehicles which can be used to manage safety and inform other road users of oncoming traffic as well as the current capacity of the traffic network.
V2X - Vehicle-to-X (nomadic devices, etc)	A form of communication within the field of CVIS. The vehicle sends data to dynamic and mobile devices which may include mobile phones, and moving nodes etc in order to maintain management of the traffic network.
VANET - Vehicular Ad-hoc Networks	A Vehicular Ad-Hoc Network, or VANET, is a form of mobile ad-hoc network, to provide communications among nearby vehicles and between vehicles and nearby fixed equipment, usually described as roadside infrastructure and traffic control centres.
VII - Vehicle Infrastructure Integration	An American term used to describe the research and development of road-side infrastructure and in-vehicle systems working together as a single unit. Safety is paramount within VII. However increasing safety is usually at the expense of efficiency, therefore VII aims to increase both safety and efficiency.
VSC - Virtual Sub-Centre	The virtual sub-centre (VSC) functions locally via the V2V communication system, processing data acquired by the vehicles and rapidly providing instructions related to local traffic and safety situations. It is based upon ongoing research for the COM2REACT project (a successor of REACT). It also transmits, by way of V2C communication, selective data to RCC and receives, in return, instructions to distribute to the vehicles. The role of VSC is set, unnoticeable by the driver, to one of the vehicles in the group according to rules imbedded in all COM2REACT vehicles.
VMS - Variable Message Sign	A variable message sign forms part of the road infrastructure in many parts of the world. It gives out general information from the status of the road to warnings and atmospheric anomalies (weather). VMS are usually situated either in an overhead or road-side format so that drivers can easily interpret the messages that are being displayed.
WAVE - Wireless Access in a Vehicular Environment	Vehicular communications and networks based on the recent wireless access in vehicular environments (WAVE) technology comes into sight as a state-of-the-art solution to Intelligent Transportation Systems (ITS), which is anticipated to be widely applied in the near future to radically improve the transportation environment in the aspects of safety, intelligent management, and data exchange services.

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"To be modern is to find ourselves in an environment that promises us adventure, power, joy, growth, transformation of ourselves and the world-and, at the same time, that threatens to destroy everything we have, everything we know, everything we are." (Berman, 1983)

Chapter 1 - Introduction

This chapter introduces the thesis via the background and problem statement, giving formal definitions of ITS. The scope of the study, project requirements, research objectives and the philosophical outline of current issues within the chosen research field are detailed. Potential risks, the perceived area of originality and the outline of the thesis is proposed which leads into an assessment of current ITS evaluative approaches and main problem rationale of the thesis in Chapter 2.

1.1 Background and Problem Statement

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 (Quddus et al, 2008; 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 despite the ceteris paribus trend between traffic flows and accident rates (Quddus, 2013), 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 are used to reflect these three aspects, as defined in subsequent sections of the thesis. 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 thesis 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 three particular types of ITS. The first is 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. These technologies have become a cost effective solution compared to alternatives such as road widening in the context of continued increases in traffic density (Sultan, 2009).

Assessing environmental and socio-economic performance of ITS by focusing on the ICT element and technologies themselves has been sparsely represented. It is predicted that ICT integration will become increasingly ubiquitous, embedded at the user oriented level through in-vehicle and automated driver systems (Caravani et al, 2006b; Ferreira and d'Orey, 2012; Keqiang et al, 2012; Li et al, 2012). This transformation poses many challenges and naturally features high degrees of uncertainty the further we forecast into the future. While some technologies are identified as having 'evolutionary' or marginal effects such as ATM (Bennett et al, 2010), other systems such as Automated Highway Systems (AHS) are more ambitious (Larburu and Sanchez, 2010). This research also aims to provide a forecasting method to effectively account for these factors, providing a decision support tool so that decision makers can prioritise areas of improvement and evaluation of ITS schemes using an integrated consequential modelling approach. The proposed framework forecasts emissions reductions and socio-economic performance for two additional key technologies of various scales up to 2050. As technology evolves into a more ubiquitous configuration it is a reasonable assumption that the installation of technology on the roadside due to ATM will recede. Early research is already demonstrating the feasibility of this approach through the use of vehicular ad-hoc networks and the integration of traffic management with cloud computing (Gerla and Kleinrock, 2011; Hussain et al, 2012; Kaur and Singh, 2012). 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, although urban implementation is out of scope for the thesis. Interviews, the opinions of various experts and dynamically weighted targets provide input to a decision support model.

The originality of the EnvFUSION method stems from a priority index which is used to ascertain overall sustainability gains and losses and is a key component currently missing from ITS appraisal due to the limited scope of current assessment practice. Current ITS frameworks only assess service performance based upon a single location rather than the whole infrastructure. In addition, different actors possess different and sometimes conflicting requirements in terms of performance which will affect their perspective of the system.

1.2 Defining Intelligent Transport Systems

The literature (Fujise et al, 2000; Gurínová, 2005; Cottrill, 2009; Žilina, 2009; Lee et al, 2010) describes ITS as an 'umbrella' term which takes into account a combination of ICT based systems and transport infrastructure to provide 'intelligent' services. The intelligence of ITS is derived from the ability to assist in or make decisions based upon a pro-reactive response to the environment. A variety of ITS systems today allow increased navigation, alertness and response to critical and non critical scenarios (Quddus et al, 2008; Skog and Handel, 2009; Li and Zhang, 2010). Examples of current ITS include VMS where messages are displayed on overhead gantries providing general traffic information including route Estimated Time of Arrival (ETA) and weather patterns within the route to alerting drivers of serious incidents such as collisions and traffic congestion. Other examples include toll collection via an electronic tag installed within the car to pay for road use and parking measures (Levinson and Chang, 2003; Boyles et al, 2010). Deakin et al (2009) reinforce certain ITS services as discreet invisible agents (services which are not obvious or undetected by the public) that assist in collecting data for traffic control centres allowing increased incident detection and avoidance. Such examples include surveillance cameras, speed sensors and adaptive traffic signals.

1.2.1 Future Vision

The future vision of ITS according to some authors (Fensel, 2007; Tuominen and Ahlqvist, 2010) leads to a greater cooperation of intelligence as ICT (Information Communication Technology) due to enhanced technical ability becomes the backbone of transport services. As technology matures, the ability of ICT to maintain transparent and ubiquitous communications between the transport network will grow more prominent allowing a safer, efficient and environmentally stable future.

Safety and efficiency of the first ITS generation has improved the traffic network (Dar et al, 2010; Tuominen and Ahlqvist, 2010; Vlassenroot et al, 2010). The second generation of ITS as discussed earlier will involve a fully ubiquitous transport service platform which includes wireless communication and sensor networks such as vehicle-to-vehicle (V2V) data transmission (Hall and Llinas, 1997; Ergen, 2005; Torrent-Moreno et al, 2009b; Heddebaut et al, 2010). Future ITS systems as mentioned above will eventually be connected through a form of VANET allowing ubiquitous communication between the actors (drivers, traffic controllers etc) of the transport network (Bilchev et al, 2004; Prakash and Tripathi, 2008; Dar et al, 2010; Ergen, 2010). Energy efficient algorithms, performance analysis and end-to-end security protection will need to be integrated to support the wireless services (Blum et al, 2004; Bharucha et al, 2009; Di Renzo et al, 2010; Nazaryan et al, 2010).

Future services may include a fully automated collision avoidance and detection system where a vehicle in front would send a signal to alert other drivers and to reduce speed via automated braking (Cacciabue and Martinetto, 2006; Gehrig and Stein, 2007; Tsugawa, 2008) as well as possible vision enhancement (Bertozzi et al, 2002). Automated platooning includes vehicles which drive on 'autopilot' and are linked via electronic connectors that allow speed and distance harmonisation for increased efficiency (Naranjo et al, 2009; Skog and Handel, 2009; Glaser et al, 2010). Integrated weather forecasting and hazard awareness will allow drivers to remain updated on environmental conditions (Caravani et al, 2006b; Manasseh and Sengupta, 2010; Santa et al, 2010). Finally, advanced traffic management systems will allow dynamic control of lanes, speed zones and road guidance (Dao et al, 2008; Vlassenroot et al, 2010; Young et al, 2010).

1.2.2 ITS Inhibitors

While ITS already includes ubiquitous elements there are several barriers which prohibit the advancement of ITS technology. Deakin et al (2009) states that: -

> *"Deployment costs, funding restrictions, liability concerns, uncertain demand, institutional inertia and political challenges have limited ITS in a certain number of cases".*

Certain technologies such as GPS for example are inaccurate for technologies such as platooning which require accuracy to within feet or even inches for successful lane guidance (Drawil and Basir, 2010; Enache et al, 2010). Recent research into quantum clock design may allow this technology to become integrated via forthcoming transmission mediums (Galileo etc) a lot sooner than anticipated provided the standards are in place (Chou et al, 2010). However, the biggest setback for ITS planning according to Kulmala et al (1999) and Newman-Askins et al (2003) has been due to the lack of suitable evaluative measurement tools and techniques dedicated to ITS systems such as sustainability, resilience, data management and general standardisation of technologies. This includes the lack of suitable historical data as road authorities require these tools to draw comparisons with plausible alternatives. ITS is now accepted as one of the primary approaches to improve transport efficiency, therefore ITS project evaluation methods need to conform to the same rigorous standards as conventional transport procedures. Newman-Askins et al (2003) and He et al (2010) warns that ITS and conventional transport evaluation are measured by vastly different variables.

For example, current transport projects are based upon economic cost and physical construction such as widening and the production of new roads while ITS is evaluated based upon socio-technical services which provide *improved* traffic flow, safety, and comfort levels. An analysis of the two types of evaluation indicates that ITS may feature a significant amount of data types which can be represented in both quantitative and qualitative modes causing disaggregation and erroneous data elements. In conclusion, there is a significant incompatibility when attempting to evaluate ITS using existing planning and evaluation approaches and would therefore prove infeasible to attempt to adapt the currently isolated evaluative approaches to measure the low carbon performance of ITS. It is here where the novel research 'story' begins.

1.3 Contribution to ITS Performance

The originality and distinctiveness of the research lies in its contribution to ITS performance management and appraisal (the background theory) via an approach to determine inter-urban ITS sustainability (the focal theory). According to Patey et al (2008) there is a paucity in research focusing on the embedded lifecycle emissions in the construction, operation and disposal of ITS schemes. In addition, what has not been identified within the ITS literature is a framework mechanism that endeavours to assess the splicing of environmental performance measures with the technical sustainability of ITS technology. This process is coupled with the additional carbon offset that these technologies attempt to administer to the transport network. At this time, the ICT support infrastructure, physical transport infrastructure and the operational assessment of vehicle throughput have all been calculated in isolation. With no clear consensus on the overall emissions that currently exist, black box 'cause and effect' chains, inconsistent emissions targets and hidden consequences remain overlooked. What is required is the introduction of performance indicators to not only monitor the potential carbon reduction while using inter-urban ITS but also to scrutinise its embedded emissions and the impact current and future ITS services have upon vehicle emissions and ICT support infrastructure.

1.4 Aim and Scope of the Study

This research aimed to develop a method to assess ITS sustainability from an inter-urban context. Urban ITS services were out of scope for this research project due to a lot of coverage already being applied to this area (Awasthi et al, 2011; Boyko et al, 2012; Kaparias et al, 2012). In the first part of the study, Managed Motorways, a UK based rural ATM service was assessed to determine the sustainable relationships between the ICT infrastructure, road infrastructure and vehicle emissions using a combination of environmental models. These include Lifecycle Assessment (LCA) and integrated decision methods including Analytical Hierarchy Process (AHP) and Dempster-Shafer theory (DST). The methods are discussed in detail in chapter 4.

The second part of the study deals with the future and adds a forecasting method with dynamic data marginalisation as the current ITS service are replaced through time, illustrating emissions reductions via estimating future technological development up to 2050. The literature (Nzouonta et al, 2009; Chim et al, 2010; Dar et al, 2010; Santa et al, 2010) refers to the future of ITS in the form of Vehicular ad-hoc networks (VANET) as the next generation for managing communication and direct traffic control, therefore the research was focused within this distinct field. The study aimed to investigate the potential of a future road network where driver visual directives (i.e. infrastructure) is minimised e.g. the absence of signage, gantries etc, particularly with respect to ITS management of ubiquitous ICT services. This future road network must reflect the need for a low carbon future and sustainability in terms of energy use and maintenance. The vision derived around ITS performance management involves the successful management of data and information being delivered to manage the transport network at an acceptable level of performance and it is an emerging discipline in its own right.

> *"The transportation system has not only been confined to the purpose of transferring people or objects, but also for the realisation of transferring service and information" (He et al, 2010).*

ITS strategies, models and perceptions of low carbon highways, their infrastructure and policies are critically assessed and evaluated. The report then proposes a wider ITS performance framework including approaches from system dynamics to determine the relationships between other socio-technical parameters for inter-scheme decision making via a super-matrix. It is envisaged that the findings from the research will highlight the current issues with regard to acceptable low carbon ITS strategies and initiatives which are pivotal in the development of future low-carbon transport solutions (Fleischmann et al, 2004; Sentance, 2009; Lee et al, 2010; Tuominen and Ahlqvist, 2010).

1.5 Research Objectives

The key goals in relation to this research are as follows: -

- Identify main weaknesses of ITS appraisal frameworks and propose solutions to reduce these weaknesses (Research objective 1)
- Evaluate current environmental analysis and decision tools for assessing the sustainability of ITS Services (Research objective 2)
- Design and develop the EnvFUSION model to assess the sustainability of current ITS services (Research objective 3)
- Design and develop EnvFUSION model to forecast the sustainability of future key ITS services (Research objective 4)
- Identify and model ITS socio-technical parameters for inter-scheme comparisons (Research objective 5)
- Evaluate the sustainability framework and relate its development in the context of the wider ITS appraisal research (Research objective 6)

Table 1.1 over the next page illustrates an overview of the research activities that took place during the course of the research project. The overarching or main objective of the research is to propose a new evaluative performance model of sustainability for the optimisation of current and future highway networks. The proposed key performance indicator (KPI) tool attempts to monitor, measure and *optimise* performance throughput (physical traffic and IT layers) using *existing* and future infrastructure. The research emphasis encompasses both a technical ICT and a highways traffic management perspective.

Research Objective	Applicable Use Case	Current Research Problem	Proposed Novel Solution	Benefit After Completion of Research Activity
RO1: Identify main weaknesses of ITS appraisal frameworks and propose novel solutions to reduce these weaknesses.	Carry out a background review of ITS appraisal frameworks and evaluate their effectiveness. Identify ITS Socio-technical variables so that criteria can be developed which can take into account sustainability.	Limited frameworks are currently available. Little evaluative work has been carried out. Lack of historical data in terms of assessing the sustainability of ITS services. Current assessment approaches in isolation	Propose a unified environmental and socio-economic framework which can assist in prioritising in terms of sustainability areas which require improvement and link isolated appraisal areas	Gained understanding of benefits and drawbacks of current ITS appraisal approaches and their procedures. Identified potential solutions in order to maximise their effectiveness.
RO2: Evaluate current environmental analysis and decision tools for assessing the sustainability of ITS Services.	Conduct a critical Review of ESAT tools including their methods, weights and tools as applied to ITS and evaluate them in terms of their potential usefulness and integration towards sustainability.	Current environmental analysis tools do not provide relationships between ICT and transport data. Tools that are standalone possess weaknesses which must be reduced. Conflicting weighting schemes.	Selected lifecycle assessment to assess embedded emissions and identified a mathematical theory of evidence to correlate opinions of stakeholders.	Improved relational awareness between ESAT models and increased accuracy of environmental assessment in ITS appraisal. Better compatibility for appraisal.
RO3: Design and develop EnvFUSION model to accurately assess the sustainability of current ITS services.	Design a study for currently implemented ITS systems for a stretch of highway within the UK and apply sustainability framework based upon the UK and EU transport emissions targets at 2020, 2030 and 2050 milestones.	Current appraisal frameworks have a variety of weaknesses which must be resolved to improve sustainability assessment of currently implemented ITS systems. These must first be identified in order to produce the appropriate solutions.	Selected the M42 highway near Birmingham as the focal area and assess the environmental and socio-economic performance of the Active Traffic Management Scheme in operation.	Improved data cohesion and integration for current ATM appraisal. Improved targets between road and ICT fields and reduced decision conflict between stakeholders. Increased historical data.
RO4: Design and develop EnvFUSION model to accurately forecast the sustainability of future key ITS services.	Design the second step of the study to perform consequential forecasting of environmental and socio-economic assessment through two key technologies. Simulate technological change.	Current forecasting methods focus on the road and improvements in efficiency than estimating environmental impact of the ICT data center and consequential modelling.	The traffic on the M42 will be forecasted up to 2050 by two key future technologies: Inteligent Speed Adaptation and Automated Highway System.	Improved forecasting of AHS and ISA technologies as applied to a congested stretch of road. Enhanced awareness of their technological feasibility,
RO5: Identify and model ITS socio-technical parameters for inter-scheme comparisons	Use system dynamics methodology to show inter-dependencies between socio-technical criteria and develop an inter-scheme comparison matrix for comparing schemes.	There is little understanding of relationships between environmental and socio-technical criteria. No relationships with standards enforced by legislation.	Develop a strategic performance framework with four key performance indicators with connected feedback loops and super-matrix	The ability to perform inter-scheme comparisons despite missing or uncertain data and thusly allowing emissions hotspots to be identified.
RO6: Evaluate the sustainability framework and relate its development in the context of the wider ITS appraisal research.	Perform deductive reasoning to determine if the research has been successful. Assess limitations that still exist. Assess the original contribution to knowledge and propose future work.	There was currently no rigorous evaluation of ITS appraisal that takes into account the emissions of ICT, embedded emissions of the road-side infrastructure and the vehicle emissions. No previous valuation of carbon mitigation.	Cross-reference the deficiencies between current ITS evaluation theory and the proposed solutions of the research and its objectives so that the level of success can be determined.	The proposed performance framework is evaluated in terms of its success and usefulness which will allow future sustainability assessment and inter-scheme comparisons.

Table 1.1: - Research Activity Overview

ITS involves a combination of ICT and transport concepts, it is therefore appropriate to understand how both perspectives relate to the implementation of ITS transport services and maintenance of ICT. The research scope takes a UK perspective but incorporates European policy and standards development.

1.6 Proposed Thesis Outline

The structure of the thesis follows a classical doctoral form encompassing the main elements of: background theory, focal theory, data theory and contribution (Phillips and Pugh, 2010). This is reflected in the sequence of the chapters which follow the progress of the research journey and documents the knowledge and understanding emerging from the research process. The focal theory forms the *story-line* of the thesis and this is supported by relevant data and arguments in terms of the overall aims and objectives of the study. The literature review is presented at the beginning of the thesis and forms the background theory to the field of study. Data theory provides justification in terms of the relevance and validity of data sources. The final element of the doctoral form highlights the contribution made to knowledge and in particular the contribution to ITS sustainability in terms of inter-urban intelligent transport.

Chapter 2 outlines the background theory, issues and gaps concerning the assessment of environmental and socio-economic performance for ITS. Although the focus of the research was upon the development of an environment and socio-economic performance framework, several other ITS performance areas were identified based upon the literature. Each performance area is discussed in terms of issues in managing existing and future highways. In addition, the literature was reviewed on how existing techniques were being used in other contexts, leading to the development of a problem rationale for the research as a whole.

Chapter 3 discusses the research methodology. The problem rationale from the previous Chapter is used to define and select appropriate research methods. Methodological issues such as the format of the case study to be undertaken are defined and research techniques in relation to data collection are proposed. Each technique is evaluated as are the approaches adopted. The research methodology is part of a focused path to completion via several steps, leading to a critical review of environmental systems analysis tools in Chapter 4 and then the creation of a large case study with multiple embedded units of analysis in Chapter 5.

Chapter 4 introduces the role and governance of sustainability as applied to inter-urban intelligent transport systems. It covers a range of different aspects relating to the goal of providing sustainable transport coupled with green supporting infrastructure for the governance and provision of Intelligent Transport Systems and services. An introduction to the challenges and perspectives of sustainable transport as well as current practices and the planning for a low carbon future are explored. An evaluation of the models and tools that support the decision making of ITS is illustrated and finally, a comparison of sustainability models are discussed and evaluated for the design of the EnvFUSION performance framework.

Chapter 5 discusses the development of the case study and data collection strategy. A method integration strategy was proposed and a large singular case study was designed which features two embedded units of analysis in the form of current and future ITS technology assessment approaches. The aim of this analysis was to estimate current ITS performance bearing the significance of the UK's and EU's legislative targets. The study attempts to analyse ITS service performance using both linear and dynamic scenarios with distinct timescales featuring three different forms of ITS service. This is to demonstrate the robustness of the EnvFUSION framework mechanism. The data collection strategy is illustrated for both types of analysis.

Chapter 6 introduces the case study (assessing current sustainable performance) based upon Active Traffic Management current 'fixed' infrastructure aimed at reducing congestion on the road network as an alternative to carbon intensive projects such as road widening. The data collection procedure with regard to environmental performance indicators is presented and the steps to the development of the study are illustrated. The results of the study are then discussed along with a sensitivity analysis of the associated weights.

Chapter 7 introduces the second part of the study (assessing future sustainability performance) based upon projected estimation of ITS technologies up to 2050. The data collection procedure with regard to expected arrival of ITS services is presented and the steps to the development of the forecasting models are illustrated. The results of the study are then illustrated including a sensitivity analysis of the associated criteria. A Cost-benefit analysis was undertaken for Intelligent Speed Adaptation and Automated Highway Systems and finally, performance indexing was performed based upon future targets.

Chapter 8 introduces the final part of the study which is to explore the relationships between sustainability and the socio-technical performance of ITS systems. A strategic performance management framework is proposed resulting in an inter-scheme comparison matrix which would be able to take into account all areas of ITS performance using a dynamic socio-technical model.

The final chapter evaluates the research project including the level of success achieved, the problems encountered and future work that will be proposed. In addition, a full understanding of the philosophical and original contribution to existing ITS performance is detailed and evaluated.

"...Due to the important role information and communication technologies (ICTs) have gained in our societies, the context of transport system and policy development has started to shift from designing road, railway or waterway lines or networks towards the development of a complex technological system largely depending on ICTs and applications" (Tuominen and Ahlqvist, 2010).

Chapter 2 - Defining Sustainability Performance for Intelligent Transport

This chapter outlines the background theory, issues and gaps concerning the assessment of environmental and socio-economic performance for ITS. Although the focus of the research was upon the development of an environment and socio-economic performance framework, several other ITS performance areas were identified based upon the literature. Each performance area was discussed in terms of issues in managing existing and future highways. In addition, the literature was reviewed on how existing techniques were being used in other contexts, leading to the development of a problem rationale for the research as a whole.

2.1 Defining Sustainable Transport

This section introduces 'sustainability' in terms of environmental and socio-economic governance within the transport field. Conflicting opinions exist regarding its definition and focus, therefore in order to develop the research problem rationale it is important to clearly define 'sustainability' and its level of focus when assessing ITS technologies.

2.1.1 Definitions of Sustainable Assessment

The term 'sustainability' has been widely applied and given many definitions. Recent literature has separated the sustainability paradigm into three key dimensions: environmental, social and economic, although there is still ambiguity in its terms of reference (Hilty et al, 2006; Matthews et al, 2007). Wallis et al (2011) argues that since the release of Agenda 21 in 1992 a great deal of effort at the regional, national and global scales has been given to the development of indicators for sustainability (United Nations, 2011). In addition, there are no universal indicator sets which are supported by theory, data collection or policy governance. This is due to ambiguity within the definition of sustainability and has led to the production of a large body of work which crosses multi-disciplinary boundaries in terms of the applications assessed. Sustainability indicator sets are currently formed by social and economic indicators brought together from matrices that focus on environmental reporting that have had little or no modification (Mitchell et al, 1995). These indicators often fall short of the level of information needed to support transport project appraisal under a low carbon future.

Sustainability is defined as the ability to maintain a certain rate or level while the ecological perspective relates to exploitation or conserving an ecological balance by avoiding depletion of natural resources (Oxford English Dictionary - Second Edition, 2006). The most common of definitions is discussed in the following passage:

> *"Development (economic and social) that meets the needs of the current generation without undermining the ability of future generations to meet their own needs." (Brundtland, 1987)*

Transport emissions are a major concern for planners, engineers and other stakeholders who wish to successfully maintain a transport network. Due to major issues such as climate change and energy depletion (the depletion of fossil fuels and other non-renewable energy sources) as well as the fallout from the economic recession in 2008, adapting transport networks within the frame of a low-carbon future is a challenging prospect. Different countries and regions possess various agendas on dealing with climate change due to their own transport and logistics configuration, therefore global standards have not been truly dealt with (Berrittella et al, 2008). Intelligent transport adds additional complexity because of the integrated ICT layer which must also be assessed from an environmental perspective. Joumard and Nicolas (2010) highlight a further three categories that sustainability attempts to achieve within the transport field:

- to help in the understanding of the running of the transport system
- to provide data for managing this system (evaluation, performance, control)
- aid decision making by ranking possible options

2.1.2 The 'Pillars' of Sustainability

The literature (Marsden et al, 2010; Wallis et al, 2011) refers to sustainability as pillars of development: economic, social and ecological/environmental. The first strategy for environmental and socio-economic assessment in the UK was conducted in 1999. It was revised by the Department of Environment, Food and Rural Affairs (2005) because individual departments focused on one or two aspects of the pillars that related to their own specific vision and goals. It was argued that the sustainability pillars should be tackled in parallel to ensure a highly focused vision, therefore additional guidelines were introduced and include maintaining environmental limits, ensuring a strong, healthy and just society and achieving a low carbon economy. Many researchers have also added a fourth pillar in order to accommodate institutions or organisations. The three pillars plus the addition of 'institutions' are illustrated in Figure 2.1.

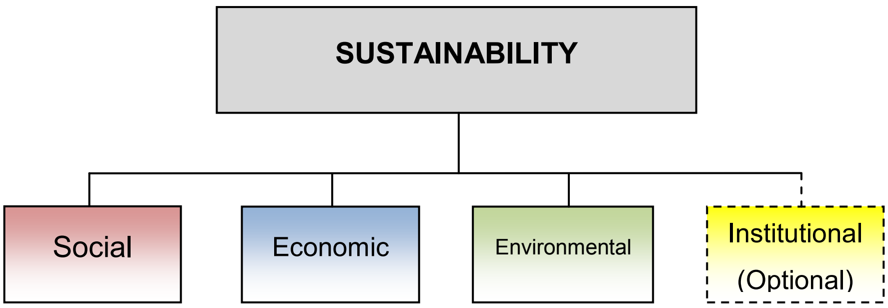

Figure 2.1: - The 'Pillars' of Sustainability

Joumard and Nicolas (2010) highlighted a noticeable shift in prioritisation of environmental, economic and social principles. Economic benefits are no longer the central priority due to recent changes in attitudes to the environment and safety. The requirement to maintain profit in transport projects is tertiary to climate change policy, social factors and a 'green' attitude to transport (Department of Energy and Climate Change, 2009a). Based upon the economic, social and environmental factors of Passets' (1979) work '*economics of the living*' the *'naturally harmonised'* model of sustainability has now resurfaced (Figure 2.2).

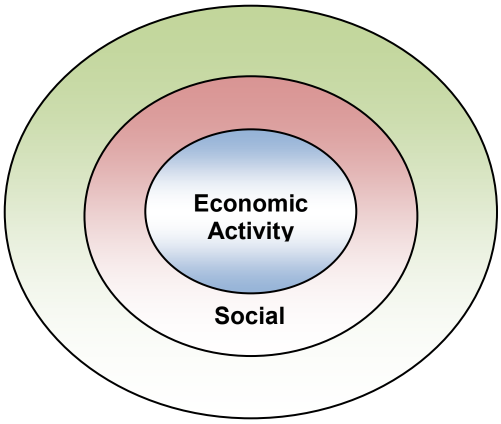

Figure 2.2: - Prioritisation of economic, social and environmental spheres (Source: Passet, 1979)

2.2 Environmental Issues

The global threat of climate change has generated an impetus for a low carbon transport future through emission reduction targets and legislation by the UK government and other global agencies (Department for Transport, 2007; Department for Communities and Local Government, 2009; Department for Transport, 2009). Coffin (2007) and Demirel et al (2008) maintain that the highway network in the UK is causing an imbalance to the atmosphere and general environment. ITS Infrastructure, such as overhead gantries which display limited traffic related information and powered signage are all carbon and energy intensive[1] (Highways Agency, 2009a). These issues are being tackled by the Department for Transport, European Commission and global agencies (ITS USA/China/Japan etc).

> *"The potential negative impacts of transportation on environment can be listed as degradation of air quality, greenhouse gas emissions, increased threat of global climate change, degradation of water resources, noise and habitat loss and fragmentation." (Demirel, 2008)*

[1] See section 2.4.4

2.2.1 Root Causes and Chemical Identification of Greenhouse Gas Emissions

The highway infrastructure has a negative impact on the eco-system and can isolate animal life forms from their various habitats therefore damaging the natural balance of life (Demirel et al, 2008; Macdonald et al, 2008). Greenhouse gas emissions are produced as a by-product of the inefficient burning of petroleum and diesel in the internal combustion engine and are contributing significantly to climate change. Despite ever increasing traffic growth, emissions are beginning to decline due to the increase in engine efficiency and fuel consumption supported by several Euro emission standards. European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states (European Commission, 2012). They are defined in a series of European Union directives for the progressive introduction of increasingly stringent standards. Currently, emissions of nitrogen oxides (NO_x), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM_{10}) are regulated for most vehicle types, including cars, light goods vehicles (LGV) and heavy goods vehicles (HGV). For each vehicle type, different standards apply. Compliance is determined by running the engine through a standardised test cycle. Non-compliant vehicles cannot be sold in the EU, but new standards do not apply to vehicles already on the roads. No specific technologies are mandated to meet the standards, though available technology is considered when setting them. New models introduced must meet current or planned standards. The general market ratio for these standards will have a direct impact when measuring emissions. Therefore any ITS performance framework developed must take the standards into account.

Figure 2.3 illustrates the trend of greenhouse gas emissions of road transport in the UK converted into CO_2 equivalency using the IPCC's Global Warming Potential methodology (IPCC, 2001). Greenhouse gas emissions include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFC's), perfluorocarbons (PFC's) and sulphur hexafluoride (SF_6). Demirel et al (2008) conducted a spatial approach to exploring the impacts of road transportation in Istanbul, Turkey. The figures illustrated that between 1990 and 2000, Carbon Monoxide (MO) had increased by 3.85 times (the highest category). In addition, HC, Nitrogen Dioxide (NO_2) and Sulphur dioxide (SO_2) increased 3.2, 1.76, 2 and 2.07 respectively from 1990 to 2000.

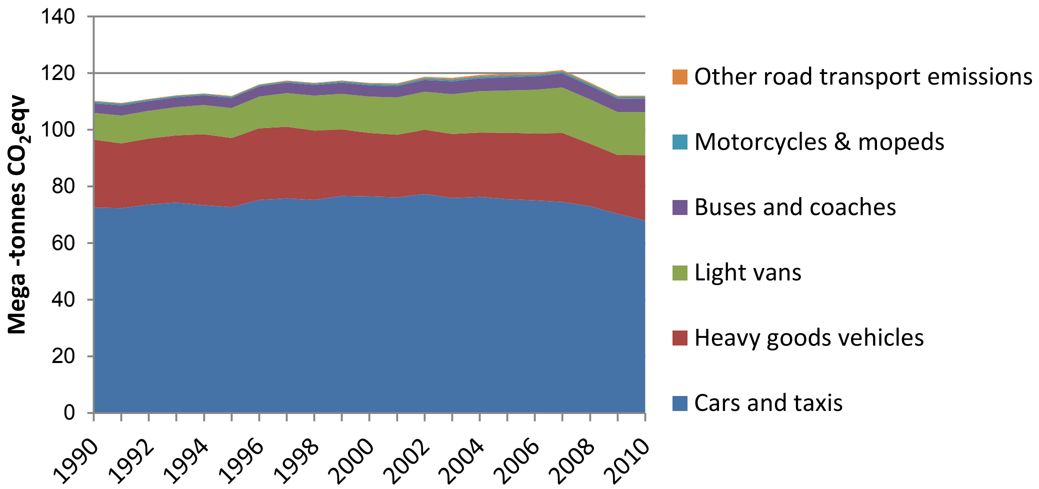

Figure 2.3: - Greenhouse gas emissions of Road Transport in UK (Source: DfT, 2013)

Grant et al (2003) highlight the increased levels of CO_2 caused by road and vehicle 'runoff' where chemical leftovers are contaminating the surrounding road-side and wider areas. Chemicals include HC, asbestos, lead (Pb) cadmium (Cd) and copper (Cu). Forman and Deblinger (2000) discuss the effects of dust passing off the road surface in relation to global highway systems. A combination of vehicle emissions and speed causes the spread of dust in environments such as deserts particularly in America and Middle Eastern highways. Further maintenance that is applied to the road infrastructure can result in a complex system of chemical exchange. The use of de-icing salts containing magnesium chloride in bad weather will spread not only through animal habitats but also into the drainage system (Grant et al, 2003; Coffin, 2007). In some cases the use of pesticides and insecticides puts a major impact on the habitats and soil, making future land use unsuitable for both nature and human colonisation.

2.2.2 Atmospheric and Habitat Degradation

Transportation is an *"artefact of culture"* according to Coffin (2007) where its destiny is entwined with the prosperity of the local community, therefore it is important that the road network is optimised by offsetting major environmental issues. In addition, roads cause other changes to the environment which may present long term damages to the ecosystem as well as the gradual destabilisation of the atmosphere. Road materials such as tarmac and concrete pavements contain a variety of chemicals which destroy the environment. Forman et al (2003) refer to the road structure as a whole (pavement, tarmac and road-side infrastructure) as *"habitat breakers"* which introduce unnatural and exotic toxins, killing animals and producing behavioural changes in various species and vegetation within a close proximity. Also labelled as de-colonisation, the surrounding land eventually becomes uninhabitable. The advantages of a low-carbon society will benefit not only people, but also the environment and eco-system as a whole (Commission for Integrated Transport, 2007; King, 2007; Department of Energy and Climate Change, 2009a). Road transport represents 25% of CO_2 emissions within the UK and approximately half of this figure derives from the energy consumption of the first generation of ITS (variables message signs) over a period of an average 15 year lifecycle (Conquest et al, 2007). Various manufacturing processes used to build gantries for ITS on highways are contributing to global warming. So far, very little work has focused on measuring such contributions.

2.2.3 Power Usage in Infrastructure

Various authors (Conquest et al, 2007; Valsera-Naranjo et al, 2009; Perujo and Ciuffo, 2010) argue that it may be costly to reduce transport emissions directly using an alternative power source within a vehicle power plant (electricity etc). The energy required to recharge the vehicles using a sole electric power plant draws energy directly from the national power grid (Valsera-Naranjo et al, 2009). In addition, the cost to implement recharging infrastructure is very high due to limited services in place (Valsera-Naranjo et al, 2009; Brown et al, 2010; Perujo and Ciuffo, 2010). Therefore transport may be the last area to receive this kind of reduction. Better management of energy through power grids may require new techniques such as the UK government's (2009) ‘IT Greening’ plan to conserve power and maintain demand while the network waits for new policies for electric vehicle adoption to materialise (Crooks et al, 2009; Brown et al, 2010; Perujo and Ciuffo, 2010). According to Holt and Pengelly (2008) gantries and other road-side infrastructure use a lot of power and feature a high carbon count which may have a direct impact on the climate. The HA refers to ATM as having a number of potential benefits when compared with alternatives such as lane widening, including cost effectiveness, speedy construction and an increased likelihood of implementation within the increased highway boundary (Highways Agency, 2009a). HA (2009a) states that temporary shoulder running provides:

> *"... an additional lane during congested periods by utilising the existing Hard Shoulder as a running lane...early indications show that this is a safe, efficient and sustainable way of creating increased capacity within the existing road space to manage changing traffic conditions."*

However, an analysis of the M42 and M25 (the latter features no shoulder usage at this time) Active Traffic Management (ATM) schemes shows 20-30% of CO_2 savings attributable to reducing congestion are cancelled through implementation and operation. 50% of this CO_2 cost could be mitigated if renewable energy sources are utilised in order to supply the operational energy consumption (Holt and Pengelly, 2008). It is critical that the energy consumption of a scheme is energy efficient in order to maximise its environmental benefit and this is therefore an important point in the discussion.

2.3 Conventional versus Intelligent Transport

The UK government and other regions around the world are working to produce low carbon transition plans (Department for Transport, 2007; Department of Energy and Climate Change, 2009a). It is therefore essential that new transport appraisal methods are developed towards a modular service based system that can be easily adapted to future social and technological trends. New methods must therefore be developed in order to cater for ITS services as a system, appraising its entire infrastructure rather than focusing solely on the effects of the highway. According to Gurínová (2005), a key difference from conventional transport planning is that ITS planning must be designed for the future welfare and benefit of a fully functional transport system, while it is arguable that traditional methods only account for current problems and are not dynamic. They cannot adapt to changing situations and must therefore be consistently reviewed for continual service improvement (CES). For example, building a road that cannot cater for any significant increase in traffic volumes. Any method or framework that is to be developed will need to take these issues into account to improve current and future performance in transport related design and development. The main transport issues can be categorised into two groups: traffic congestion and traffic accidents based upon injuries and fatalities. For traffic congestion, possible solutions include increasing highway capacity, increase passenger throughput and reducing demand. Traffic accidents may be resolved through improving safety.

Table 2.1 illustrates a comparison between these two timescales, from a conventional and ITS perspective.

Problem	Possible Solutions	Conventional Approach	ITS Approach
Traffic Congestion	Increase highway capacity	New roads and road widening	Active traffic management and cooperative vehicle infrastructure systems Electronic toll collection Automated highway and driver assisted systems
	Increase passenger throughput	High occupancy vehicle lanes Car sharing Single OD route	Real-time ride matching Integrate transit and feeder service Flexible mode transit Personal rapid transit
	Reduce demand	Flexi-time programs	Telecommuting Other telesubstitutions Transportation pricing
Traffic accidents, injuries and fatalities	Improve safety	Improved roadway geometry	Partially and fully automated vehicle control systems, Automated Highway System
		Improved sight distance	Intersection collision avoidance
		Traffic signals	Automated warning systems (Virtual Traffic Lights)
		Reinforced left hand turns at crossroads	Vehicle condition monitoring
		Grade separate crossings Driver training	Driver vision enhancement
		Monitored checkpoints	Advanced grade crossing systems
		Lighten dark roads to improve visibility/better lighting	Automated detection of adverse weather and road conditions, vehicle warning and road crew notification
		Reduce speed limits/speed cameras in problem areas	Automated emergency notification: (Intelligent Speed Adaptation)

Table 2.1: - Comparison of Traditional and ITS Planning Approaches (Source: Gurínová, 2005)

2.3.1 Increase Roadway Capacity

In order to increase road capacity, conventional approaches included the building of new roads and lanes. While this was feasible early on in the transport networks lifecycle, new legislation in environmental and socio-economic perspectives and the reduction in space means road widening is becoming a limited option (Coffin, 2007;

Conquest et al, 2007; Committee on Climate Change, 2008; Department for Transport, 2009). In order to increase traffic throughput in today's road network it is necessary to focus on increasing efficiency using existing infrastructure.

ITS approaches include ATM (currently being implemented internationally) as well as more advanced systems such as Cooperative Vehicle Infrastructure Systems (CVIS) and Driver Assistance Systems (DAS). Real-time communication should be achieved through wireless networks (Torrent-Moreno, 2007; Dar et al, 2010). Incident management allows traffic management to respond immediately to emergencies such as collisions and breakdowns. Electronic toll collection, according to Levinson and Chang (2003), would assist in the reductions in delay and staff needed to maintain fixed toll routes such as bridges etc. Finally, advanced vehicular systems such as platooning allow a highly optimised state of traffic flow via assisted or fully automated control in vehicles (Shladover, 2005; Michaud et al, 2006; Hsu and Liu, 2008; Li and Zhang, 2010).

2.3.2 Increase Passenger Throughput

Traditionally, in order to increase passenger throughput several solutions were available. The literature (Menendez and Daganzo, 2007; Daganzo and Cassidy, 2008) states that High Occupancy Vehicle (HOV) lanes are dedicated to vehicles that maximise their capacity through car pooling. Advantages include faster travel times as priority is given to HOV's compared with Low Occupancy Vehicles (LOV). Single Origin-Destination (OD) routes are used to standardise the network on major road sections, however they struggle to accommodate the wide variety of characteristics[2] that vehicles possess. ITS approaches include real-time ride matching where passengers access services dedicated to finding other passengers with similar OD preferences. Users can access this information from the internet, telephone or mobile devices (Guan, 2007). Other solutions include an integrated transit and feeder service, as well as flexible and personal mode transit. Intelligent vehicle navigation according to Quddus et al (2008) facilitates an unprecedented capability to gather data both in terms of quality and quantity that are required for effective planning in future service provision although it still struggles to support mission critical applications, particularly those which support higher navigation accuracy, continuity, quality (integrity), reliability and availability.

[2] The characteristics of vehicles such as weight, speed, mileage etc differ depending on the manufacturer, model and version.

2.3.3 Reduce Demand

In order to reduce demand, various flexi-time programs have been introduced (Boyles et al, 2010; Iseki and Demisch, 2012) . An example of a UK based flexi-time program is currently in operation within central London where a colour-coded pass allows travel on a certain day of the week (Transport for London, 2008). This alternative approach, while not distinctly connected to ITS transport services does impact demand. Telecommuting has been a viable option since the early 1990's where flexible work arrangements allow employees to remain on a single site (home office etc) without the need to commute to the work place. Transportation pricing is another viable option and can be categorised through attributes such as congestion, value, peak-period, time of day and variable pricing (Boyles et al, 2010).

2.3.4 Improve Safety

Conventional methods improve safety by adjusting road geometry such as the angle of turn, gradient and lane width. The strategic placement of traffic signals allows drivers to interpret danger from a greater distance. Reinforced left hand turns at cross roads and graded separate crossings prevent vehicles from cutting in from a different lane. Enhanced driver training delivers better understanding of what to do in an emergency as well as precautionary guidance to assist in every day travel safety. Monitored road checkpoints increase enforcement to make sure drivers are fit to drive and alert them of obstacles ahead. Finally, speed cameras can be deployed to encourage drivers to adhere to the speed limit and drive more carefully. One of the key goals of ITS is the successful implementation of safety protocols. These protocols exist to improve the safety and wellbeing of drivers as well as to increase driver comfort (Abdel-Aty et al, 2008). However, some authors (Shladover, 2007; Tsugawa, 2008; Amditis et al, 2010a; Amditis et al, 2010b; Schubert et al, 2010) refer to more advanced technologies such as automated driving and DAS that may enhance road safety.

Information under load (lack of attention due to over-automation) suggest that potential technologies should be reviewed. According to Santa et al (2010), Su and Ordys (2010) and Mitropoulos (2010), collision avoidance support systems (CASS) are one of the main topics to be reviewed and standardised. Current research deals with the navigational and communication aspects of the technology, two sub-systems which determine the performance of CASS technology. Automated warning systems will provide the same services as gantries which give weather, traffic and other environmental updates to the driver, although the information is presented on-board which reduces the need for road-side infrastructure. Driver vision enhancement features include on-board vision systems capable of enhancing vision, such as night vision etc. According to Young et al (2010) and Luo et al (2010), Intelligent Speed Adaptation (ISA) and Adaptive Cruise Control (ACC) will assist in the reinforcement of speed limits within rural areas and may also reduce fatalities and injury. This technology automatically maintains the speed of the car within the maximum speed limit. ITS implementation and evaluation differs from other conventional transport projects (Newman-Askins et al, 2003). This is due to unique data types and variables that form part of an ITS system. Currently there is no main framework backed by policy to evaluate ITS systems through conventional transport methods. There is also a large degree of informational complexity evident in future technologies such as vehicular networks where data must remain valid and secure to users at a specific time and location (Haynes and Li, 2004).

2.4 Evaluation Procedures in ITS Projects

This section explores the literature on the current evaluative processes that relate to ex-ante and ex-post performance monitoring of ITS projects.

2.4.1 Factors in Implementation

Currently, a limited amount of historical data exists in order to conclude whether certain ITS projects will be successful (He et al, 2010). This is because certain ITS impacts (according to Newman-Askins et al (2003)) are problematic to quantify since driver comfort and travel reliability are qualitative. In addition, little work has been carried out to explore the relational attributes of ITS projects and their associated impacts, making it difficult to transfer the results in space and time. ITS evaluation must be maintained at the same standard as conventional transport projects. Therefore an appropriate framework must be created in order to integrate ITS evaluation methods into the existing transport planning methodology (Gurínová, 2005).

The Implementation process for an ITS system is affected dynamically by different actors (Bekiaris et al, 2004). Three actor groups (Users, Manufacturers and Authority) determine the dynamics of Implementation. The road user plays a role in initiating consumer demand through to accepting the service depending on the role the service will attempt to complete. Bekiaris et al (2004) states that: -

> *"The users' willingness to pay is not the only thing affecting the release of new technologies. There might be bottlenecks in the domain of regulations, insurance or standards or it might be even forbidden to release certain ITS products under the current laws."*

The second group of actors includes vehicle and system manufacturers. They possess the highest level of knowledge on technological competence of the proposed systems. However, product development (research) is partially dictated through the end users' needs and whether they are willing to pay for the new service. Manufacturers are dependent upon legislation and are bound by specific rules and regulations. The third group of actors includes the authorities, legislation and administrative practices. Their goal is to protect the welfare of users through considering new system implementations and the overall impact that the new technologies will have upon society (users and non-users) as well as making sure their policy operates within legal consensus. User opinions may direct the implementation of the service. Figure 2.4 illustrates the actors affecting the final implementation process.

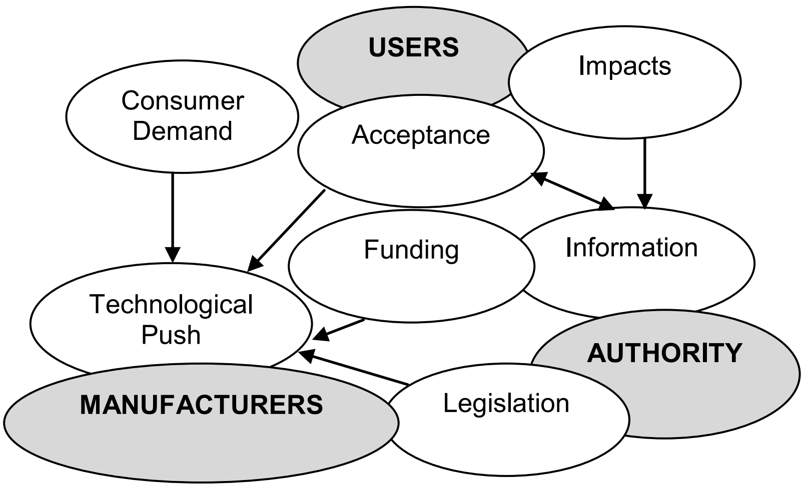

Figure 2.4: - Actors affecting Implementation (Source: Bekiaris et al, 2004)

Grant-Muller and Usher (2013) developed a propensity model to determine whether ITS services provided environmental and economic benefits. Firstly, underlying drivers and a synthesis of empirical evidence was applied to determine whether such systems can be developed and secondly, whether policy priorities amongst national and international stakeholders reflect a propensity for ITS deployment in order to yield those benefits. The results indicated that ITS can reduce the carbon intensity of negotiating distance, however, the evidence base concerning the real-life environmental and climate change related impacts of ITS systems isn't yet at the required level of detail or routinely and rigorously collected to fully support investment and related policy decisions. Future challenges included an acknowledgement of the enduring strategic priority of both economic and environmental sustainability, particularly in the post economic recession. coherent cross-sectoral policies at national (and where appropriate international) level, that allow full evaluation of ICT related measures which impact beyond the transport sector. a governance structure that is sufficiently flexible to support financial investment and maintenance that may vary in scale between different types and configurations of ITS. The findings reveal a need for a better understanding of ITS benefits. Communicating cross-sectoral synergies in terms of benefits and solutions is also a necessary element to this. The models offered a novel policy tool that may be used in practice in sustainable policy development at both national and regional level, for example in identifying countries and regions where more targeted and tailored support to the development of ITS strategies (within the context of wider transport and other sectoral strategies) could take place.

2.4.2 Quantifying ITS benefits

Social, economic and environmental impacts are unpredictable therefore their risks and costs are difficult to envisage. Some authors (Amditis, 2004; Barceló et al, 2005; Dion et al, 2010; Su and Ordys, 2010) have attempted to measure the influence of ITS through simulation (including virtual reality/virtual environment tools). However, other authors (Schade et al, 2003; Stevens, 2004) have attempted to utilise existing transport appraisal tools such as Cost-Benefit Analysis (CBA)[3] to determine the impacts of ITS. The disadvantage of applying CBA to the environmental elements specifically to ITS is that the discount rate that is applied to tangible assets is also applied to estimate the impact of emissions. Environmental impacts should be assessed separately regardless of timeframe (Kula and Evans, 2011). Others have measured ITS performance over three different approaches including delay cost, fuel cost and emission modules. The influences according to Thill (2004) were measured before and after the system. From an ICT perspective, ICT project selection is based upon an evaluation of qualitative and quantitative objective measures such as business goals, benefits, project risks and resource allocation (Asosheh et al, 2010). These measures illustrate a direct parallel when attempting to select suitable ITS projects. The research in ICT project evaluation is significant but made more difficult due to socio-environmental priorities.

2.4.3 Proposed ITS Evaluation Methodologies

The current literature proposes various solutions to measuring ITS impact internationally. The literature implies that the evaluation process of ITS projects

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[3] A review of CBA applied to ITS has been conducted in Chapter 4, Section 4.3.1.

should differ from evaluation methods used for traditional road projects. Newman-Askins et al (2003) argued that the cause and effects relationships between service components are more complex than measuring components in isolation. Newman Askins et al (2003) states the most important criteria for an effective ITS methodology are as detailed below:

- The evaluation should be transparent and allow for simple updating of impact parameters.
- The methodology should provide an accurate output as well as being objective without bias.
- Should allow comparison of results of evaluation of ITS and conventional transport projects.
- Evaluation should include rigorous sensitivity testing and not apply false precision to the estimated impacts.
- Should consider the combined effect of implementing various combinations of ITS.
- Methodology should avoid double counting of benefits.
- The base and project cases studied should be based on the same operational conditions

An ITS evaluation methodology must be capable of evaluating the impacts of individual components of the project as well as the impacts of various combinations of components. For this reason, an ITS evaluation methodology must be more sensitive and detailed than existing evaluation models due to the relational dynamics of the ICT equipment, the road user and the vehicles. It is important to note that the ITS service implementation is not just represented in a singular location but that it may span multiple geographical areas. For example, ATM infrastructure is controlled from a traffic control center (TCC) which may be based many miles away. It can then be argued that an environmental and socio-economic analysis should also take into account the energy requirements of the data center residing in the TCC as well as the effects of the ITS scheme on vehicle emissions. This is an important point in terms of creating a problem rationale for this research, in that the assessment of ITS should be performed at the system level, regardless of geographical location.

When selecting an appropriate method of evaluation for ITS projects, it is important that the balance exists between complexity and cost of evaluation as well as the cost of the potential project. The main barrier to performing a successful ITS evaluation is the lack of historical data. Very little exists due to the evolving nature of ITS projects and differences between technologies (Newman-Askins et al, 2003). It was suggested that ITS projects are merely enhancements to increase efficiency to the network and it may not be necessary to anticipate a full economic analysis. When forecasting future technologies, the economic analysis should be performed at the system level, taking into account additional vehicle costs, ICT and roadside infrastructure as well as the energy consumption of the service. It is therefore preferable to analyse the benefits of environmental and socio-economic analysis using conventional appraisal methods such as CBA or MCA, although environmental aspects should be accounted separately from other benefits which is a critical factor in the creation of an ITS performance framework. As an example, He et al (2010) proposed an ITS evaluation framework[4] for measuring the advantages of an urban ITS management and command system in the city of Beijing. The framework is illustrated in Figure 2.5.

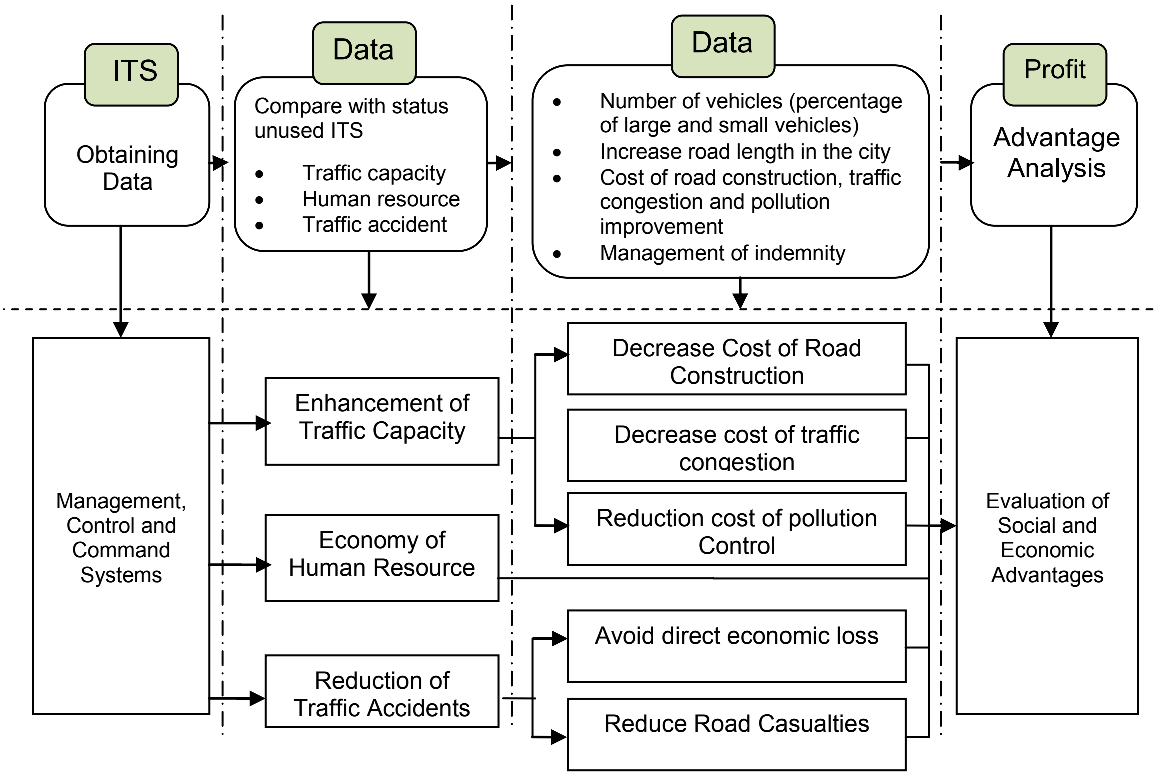

Figure 2.5: - ITS Evaluation Framework for Beijing Road Management (Source: He et al, 2010)

[4] Note that while the framework features some aspects of urban transport evaluation, the framework could still be adopted as a suitable tool for evaluating ITS in an inter-urban mode. This is because the five performance variables (reduction indicators) still apply to highways management.

Firstly the most important indexes are chosen to compare traffic systems performance ex-ante and ex-post for the ITS project to be implemented. According to He et al (2010) indexes can be obtained from official sources early and they can also illustrate the advantages of ITS implementation. In their research, the enhancement of traffic capacity, the economy of human resources and the reduction of traffic accidents are indexes of ITS. Because the units of these indexes are very different in terms of values they cannot be easily implemented as a whole. Therefore they recommend the indexes be turned into economic advantages. For example, the enhancement of traffic capacity will arguably allow the saving of cost in road construction, traffic congestion and pollution control. This is currently a major issue not only in ITS but also transport economic evaluation, in that multiple data types must be converted to an economic value in order for the evaluation to be relevant. The proposed framework in this research had to be developed in a way that could combine data with different values and hence is a key statement within a plausible problem rationale.

The application of ITS will arguably save the cost of law enforcement and emergency services. Traffic accidents will decrease due to the use of an intelligent traffic management system. Finally, the reduction of traffic collisions will bypass direct economic loss and reduce the fatality rate. ITS social and economic benefits can be calculated through the accumulation of economic benefits within the indexes. A closer analysis of the framework may take into account the levels of pollution. However, it is still quite ambiguous. It ignores the direct energy usage of the infrastructure and instead focuses primarily on economic benefits, neither does it take into account the energy requirements of the data center that communicates with the electronic equipment. A common argument with existing ITS performance frameworks is that they only cater for specific technologies in unique circumstances. They do not support continuous evaluation and service improvement of an ITS service's compatibility towards a low-carbon environment and as a result, no indication of perceived environmental benefits.

Kaparias et al (2012) and Eden et al (2012) as part of the EU project CONDUITS proposed a framework for urban traffic management and ITS. Key performance indicators were developed focusing on traffic efficiency, safety, pollution reduction and social inclusion, and the last stages of the project saw its validation through its application to four case studies. The framework also supports forecasting through the implementation of various policies and technologies enabling transport authorities to evaluate them before making a decision. However, the same weaknesses arise, such as a high level of ambiguity in the total emissions of the ITS scheme, a lack of analysis of energy emissions and finally, no assessment of the embedded emissions.

2.4.4 Studies of Inter-Urban ITS Evaluation

Within an inter-urban context, a limited number of studies have been carried out which assessed the integrated techno-economic and emissions reduction of future ITS rollout (Jun and Chunlu, 2004; Psaraki et al, 2012). Jun and Chunlu (2004) proposed a hybrid evaluation methodology for ITS deployment. The benefits were seen to be the explicit inclusion of travel behaviours in evaluation and evaluating the long-term impacts of ITS. Psaraki et al (2012) assessed the collective impact of in-vehicle technologies under the banner of driver assisted systems. These included adaptive cruise control, intelligent speed adaptation, AHS and commercial vehicle operations within the road network of the EU-27 countries. They concluded that AHS was found to be the most promising technology for increasing capacity and reducing CO_2 emissions (by 20%). This was based on a capacity throughput of 4,300 vehicles per hour per lane, while commercial vehicle operations was the most economically affordable, although they did not perform a full CBA, instead opting for a cost effectiveness analysis.

A comprehensive range of smaller studies have been carried out which aim to explore the individual attributes of inter-urban ITS. The most consistent findings of past research is that AHS offer the most promising benefits in terms of capacity improvement and safety which use algorithms and microscopic simulations to examine capacity when vehicles are organised into platoons (Hall and Chin, 2005b; Caravani et al, 2006a; Michaud et al, 2006; Fernandes and Nunes, 2012; Jaworski et al, 2012). Jarwoski et al (2012) developed a microscopic traffic simulation tool which allowed for the assessment of different traffic control algorithms. The nanoscopic components allowed more detailed observations and the measurement of parameters, such as fuel consumption that are not easily obtained in most of existing microscopic simulators. Hall and Chin (2005b) focused on grouping vehicles by destination in order to increase the travel distance between different platoons and the resulting capacity.

In terms of safety and acceptance (Suzuki and Matsunaga, 2010; Fernandes and Nunes, 2012), Kulmala (2010) proposed a framework based on nine ITS safety mechanisms as well as the requirements set to the framework. A method based on the framework and the results from applying that method for twelve intelligent vehicle systems in Europe. The framework and method cover all dimensions of road safety, also exposure or the amount of travelling, which is frequently overlooked in the safety assessment studies. Fernandes and Nunez (2012) proposed new information management techniques to help improve the stability of the platoon as well as quicker responses to emergencies such as collisions and loss of control. Algorithms using anticipatory information from both the platoon leader and the followers significantly impacts the stability of the platoon. The simulation results suggested that the effects of communication delays from sending data to the recipient may be almost completely cancelled out due to a reduction in processing time. Lai et al (2012) estimated that up to 25% of non fatal accidents would be reduced as well as 30% of fatal injuries. Suzuki and Matsunaga (2010) revealed that macroscopic shockwave propagation occurs even at a microscopic car-following level and that the speed of shock propagation can be used as an index to evaluate the safety of car-following. Bertolazzi et al (2009) as part of the EU project PReVENT developed an integrated system composed mainly of ISA speed restriction and ACC technologies. The system only intervenes when the vehicle in front is too close or objects have been detected within the path of the vehicle. The results show that prompt reactions and significant speed correction is carried out before getting into really dangerous situations, with user acceptance being high.

Emissions reduction using ITS is covered in (Bell, 2006b; Sultan, 2009; Carslaw et al, 2010; Tsugawa and Kato, 2010; Kamal et al, 2011; Liimatainen, 2011; Khayyam et al, 2012; Lai et al, 2012). Grant-Muller and Usher (2013) as part of their study on assessing the environmental benefits of ITS carried out an assessment of the potential emissions reduction of different service types. Table 2.2 over the next page illustrates the findings from various reviews, field trials, simulations and observations including additional material from the research contained in this thesis. Chapter 4 builds on this review in more detail, categorising the review of benefits that were carried out using a variety of different environmental analysis tools.

Bell assessed quantitatively and qualitatively how vehicle technologies and ITS reduce emissions and improve health. The paper specifies a set of measures, i.e., traffic signal control, demand management, road pricing, speed limits, traffic calming and vehicle control systems to achieve this goal. Tsugawa and Kato (2010) presented various ITS approaches for significant energy savings and emission mitigation, demonstrated by field or experimental data. The authors concluded that vehicular communications play an essential role not only in safety but in energy savings as well. Results from the analysis of ISA by Lai et al (2012) estimated 16 million tonnes of CO_2 could be saved in addition to 25.5 billion litres of fuel. They did not include vehicles weighing over 3.5 tonnes due to their speed being restricted to 100 km/h.

Study	ITS scheme	Data collection method	Study location/ context	Reported inter-urban benefits
(Santos et al, 2010)	Teleworking	Review of studies and modelling	UK	2.4% of carbon emissions from cars in UK may be reduced due to teleworking by 2050.
(Gross et al, 2009)	Teleworking	Expert review	UK	Inconclusive and recommendation that more detailed research is needed.
(Santos et al, 2010)	Personalised travel planning	Field trial	Japan	A personalized travel planning system helps commuters choose Environmentally friendly routes and modes; reduces carbon dioxide emissions by 20%.
(Sultan, 2009)	Active traffic management and variable speed limits	Simulation and Observation	UK highways: M42 and M25	M42: most vehicle emissions reduced by between 4% and 10%. Fuel consumption reduced by 4%. Similar findings obtained from two other studies of VSL on M25.
(Barkenbus, 2010)	Eco-driving	On-board monitoring	USA, Denver, Normal Driving Conditions	6% CO_2 emission reduction.
(Santos et al, 2010)	Eco-driving	Review of studies	Field trial	Average 10% reduction in carbon emissions.
(Carslaw et al, 2010; Lai et al, 2012)	Intelligent speed adaptation	Field trial using instrumented vehicles and emissions models	UK (Leeds and Leicestershire), different road types	3.4% CO_2 reduction for voluntary (user controlled). 5.8% for Mandatory (legal enforcement).
(Barth and Boriboonsomsin, 2009)	Eco-driving: dynamic systems that utilise RTTI	Simulation	Simulated environment	Reduction in carbon emissions and fuel consumption by 10%–20% per cent without a significant increase in journey time. Real world experiments showed similar but slightly lower findings.
(Santos et al, 2010)	Eco-driving	Field trial	Netherlands: 1999-2004	Fuel consumption reduced between 0.3%-0.8%.
(Smokers et al, 2006)	Driver assistance systems	Review of studies	Europe	5% to 25% carbon saving with 10% generally agreed.
(Zabat et al, 1995; Dávila and Nombela, 2010; Psaraki et al, 2012)	Platooning and road trains	Laboratory testing and on-field triads	Global	Average reduction of approx. 20% of CO_2 emissions and fuel consumption.

Table 2.2: - Environmental benefits of ITS Schemes (Source: adapted from Grant-Muller and Usher, 2013)

For voluntary ISA (the ability to activate speed restriction on command) this related to a saving of 3.4% of CO_2 and 5.8% when mandatory ISA (permanent speed restriction) is active. Khayyam et al (2012) developed an adaptive cruise control 'look-ahead' energy management system. The evaluation outcome indicated that the vehicle speed was efficiently controlled through the look-ahead methodology based upon the driving cycle, and that the average fuel consumption was reduced by 3%.In Liimatainen (2011) and Kamal et al (2011) the authors acknowledged the importance of driver behaviour on fuel consumption and associated pollutants emissions, proposing eco-driving schemes or incentive systems that decreased fuel costs and pollutant emissions.

Other research has explored the cost of implementing ITS (O'Dea, 1999; Carsten and Tate, 2005). Early research such as O'Dea (1999) indicated AHS without a significant amount of road tolling would not be preferred over conventional highway operation. Carsten and Tate (2005) concluded that implementation of ISA could produce benefit/cost ratios over a 60-year period of either 3.4 (for a market driven future scenario) or 7.4 for a regulatory future scenario, based on the Department for Business Enterprise and Regulatory Reform Central scenario for fuel prices. The costs of deploying ISA are larger in the earlier years and the benefits come later when more vehicles have ISA. However, the payback time was not very long. The benefits would outweigh the costs by 2025 under both deployment scenarios.

2.4.5 Green ICT Policy

ITS performance evaluation should incorporate the emissions and energy consumption of the ICT architecture connected to the schemes. While it is important for the transport system (including road-side infrastructure and eventually vehicles) to be enhanced by measures implemented in order to achieve a low-carbon vision, it is also necessary to measure and maintain a carbon neutral data management system (Cabinet Office, 2009; Christensen, 2009; Riaz et al, 2009; Seungdo et al, 2009). According to Shah (2009) the future market for green IT services will exceed three billion pounds by the end of 2013. The use of ICT within intelligent transport provides an integral platform to implement and maintain advanced traffic services. ICT infrastructure that is directly involved in maintaining ITS must also be environmentally balanced (Ho-Jin and Jong-Tae, 2009). For example, Variable Message Signs and other infrastructure used by ATM are controlled via a regional traffic control center through data linkage. A data center is used to store control systems which in turn requires energy to operate and must therefore be taken into account to ensure the emissions estimate is accurate. An ICT 'greening' plan has been developed by the government in order to address these issues (Cabinet Office, 2012). According to the Cabinet Office (2009) it was proposed that by 2012 the use of ICT by the governments Central Office Estate will become carbon neutral[5]. Since the UK has an overall target to reduce greenhouse gases by 26% or more by 2020 and 80% by 2050 it is essential to ensure all elements that contribute to climate change are accounted for. The Government recently introduced a Director General post of Chief Sustainability Officer (CSO). Governmental objectives now include performance indicators for achievements against SOGE targets. It is hoped that by 2020 the government will aim to achieve a carbon neutral ICT lifecycle.

> *"This will cover carbon neutrality and sustainable processes for use of materials, water, accommodation and transport, in the manufacture, use and disposal of ICT" (Cabinet Office, 2009).*

ICT is perceived by Crooks et al (2009) as a main source of providing organisational efficiency and can directly enable mass reduction in carbon offsetting by increasing performance in decision-making and resource management. According to Feng et al (2010) and Crooks et al (2009), energy consumption from data centres is argued to be at least or greater than the carbon footprint from the aircraft industry (800 tonnes or roughly 2% of global emissions).

In relation to ITS, the methods and approaches proposed by the British Computing Society are equally important in determining how energy efficient current and future transport systems will become. A model is introduced which analyses the energy output of a vehicular network using the Geographical Adaptive Fidelity (GAF) management protocol. The overall goal of their research was to provide a model for a software utility which would control the energy consumption of vehicular networks. Since the networks are ad-hoc, certain transceivers (estimated to be between 25 and 40 mAh) that are not connected to the vehicles must be placed within the infrastructure. They require their own power supply to function which will increase the level of energy required. The Committee for Climate change (2008) predicted that climate levels will have peaked by 2016 but should begin to fall based upon the distribution and implementation of new technologies.

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5 These targets form part of the governments Sustainable Operations on the Government Estate (SOGE).

2.5 Problem Rationale and Framework Requirements

In order to satisfy the first research objective (RO1) a problem rationale was proposed leading to the research methodology in chapter 3. It is acknowledged that ITS represents the future of the transport network, aiming to enhance rather than revolutionise its operation. The ability to understand the integration of conventional transport and ICT based systems from the perspective of socio-economic and environmental performance is complex. These issues must be identified in order to formulate solutions in the development of an integrated ITS sustainability performance framework. The modern approach to developing standards and robust technologies must be judged from environmental, social and economic perspectives[6]. This stance is reinforced by climate change legislation leading to the need for a low-carbon road network, providing the foundation for the research conducted in the thesis.

2.5.1 Level of Focus

It is apparent that current ITS appraisal frameworks only assess services based upon a single location rather than the whole system. They do not take into account components that are located off the physical road space. For example, when assessing the contribution of emissions savings of ATM, the Highways Agency did not take into account the emissions of the data center used to control the road-side infrastructure (Mott Macdonald, 2009). Assessing performance at the system level (taking into account all services that are linked to the ITS scheme rather than focusing on a single geographical area) would allow the contribution of emissions and energy consumption to be more accurately reflected in the analysis of system performance .

The review of the literature also indicated a lack of emphasis being placed on performance between the actors of the ITS service. Different actors possess different and sometimes conflicting requirements in terms of performance which will affect their perspective of the system. Therefore an analysis of social, economic and environmental output between the actors (road network operator, manufacturer etc) will improve estimates of performance for future ITS technologies such as ISA and AHS. This is due to each technology being configured in a vastly different fashion although their overall aims are similar in terms of reducing traffic congestion and improving traffic safety. It is also difficult to assess the performance between schemes due to differing configurations in technology, scale and cost. Performance

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[6] Refer to Journard and Nicolas (2010), Chang and Chen (2009) and Passet (1979) for more discussion.

could be assessed regardless of differences in configurations and scope of the technologies. The ability of transport and ICT services to operate under a low-carbon future requires analysis from these perspectives. As He et al (2010) highlighted, a lack of historical data when assessing future performance of ITS requires a reliance on very limited real-world studies. The performance frameworks evaluation process should include rigorous sensitivity testing and not apply false precision to the estimated impacts.

Finally, index values used in current appraisal frameworks are monetary due to the difficulty arising in combining different value types into an absolute whole. One solution is to weight each index value with a priority value so that a combination of different values could be normalised through a holistic performance indicator. An inter-scheme comparison super-matrix containing ITS performance indexes between schemes could then be generated. When monetising the environmental cost savings using traditional methods, the results are inaccurate due to use of a single discount rate applied over long time periods, when in reality they can only assess environmental aspects in the current timeframe when using methods such as CBA. The proposed framework would ideally apply dual discounting for future ITS schemes in order to measure environmental cost savings for periods of more than 20 years, especially when forecasting into the future.

2.5.2 Environmental Issues

According to HM Governments Department of Energy and Climate change (2009), the transport sector should contribute a saving of 19% on CO_2 emissions between 2018-2020 based on 2008 levels. Sentance (2009) proposes that in the same year there is also a possibility for carbon reduction through improving the technical efficiency of vehicles (including vehicle throughput and engine performance). King (2007) proposes that by 2030 vehicle power plants will be 50% more efficient in terms of CO_2 emissions (based on 2007 levels) if current trends are followed. According to Sentance (2009) and Eddington (2006), the majority of the transport infrastructure will be utilised for future ITS iterations and will still be operational by 2050 (albeit through sufficient maintenance and restoration). However, considering one of the goals of the research is to reduce the use of traditional infrastructure, the cost of maintaining future infrastructure should be kept to a minimum. This is an indication from the literature that the limitations of space, maintenance costs and environmental issues with traditional infrastructure (tarmac roads) and widening, results in such approaches becoming unfeasible in the future. Therefore the performance framework should also assess the embedded emissions of alternative and future ITS services.

According to Patey et al (2008), no studies at that time and even now have focused on the embedded lifecycle emissions in the construction, operation and disposal of ITS schemes. For this research, the emissions from ICT and infrastructure for their whole lifecycle need to be considered alongside the potential gains through traffic flow efficiency. As the majority of future emission targets are aimed at reducing the level of CO_2 to a certain degree, environmental accounting frameworks do not take into account other GHG emissions which results in an inaccurate contribution of the ITS scheme to climate change. Converting greenhouse gas emissions into Global Warming Potentials (GWP) would increase the accuracy of the ITS schemes contribution to climate change. ICT works as an enabler within ITS systems in order to improve the performance of the road network by improved control and supervision. As discussed in the previous sections there is very little evidence to date of a framework designed to assess the combination of environmental performance with the wider impacts (such as safety and social aspects) of ITS technologies. There is currently no standardised methodology for integrating emissions of the infrastructure, ICT and vehicles into the overall analysis. A strategy is therefore needed to Integrate the environmental lifecycle results of the ICT data center, vehicle emissions and embedded emissions of road-side infrastructure to provide a cross-sectional contribution of total emissions generated from the ITS service.

2.5.3 Socio-Technical Issues

Some authors maintain that a future transport network (Valsera-Naranjo et al, 2009; Žilina, 2009; Vu et al, 2010) will consist of a variety of integrated wireless communications delivering seamless real-time data to the transport network. Transmitting this data becomes complex due to a wide variety of data types and transmission sources (Reijmers et al, 1995; Shladover, 2005; Tarte et al, 2010). In addition, these data sources need to be protected against malicious attacks (viruses, hackers etc) by maintaining its integrity (Raya and Hubaux, 2005). To achieve this, several factors must be taken into account: -

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

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

2.5.4 Performance Categories

Performance management in ITS must take environmental issues into account in order to assist in the reduction of climate change. Low carbon manufacturing processes resulting in the creation of ITS infrastructure should be in place to negate the effects of GHG emissions and energy wastage (Commission for Integrated Transport, 2007; Brown et al, 2010). The UK governments targets of not only reducing transport but also applying pressure on providing a 'green' ICT energy consumption means maintaining a low carbon future is a high priority (Cabinet Office, 2009; Crooks et al, 2009; Ruth, 2009; Feng et al, 2010). Additional performance measures are needed to estimate the success of carbon and energy initiatives within ITS (Transport and ICT perspectives) in order to achieve the goals for the future. Performance in ITS also requires a certain level of adaptability. Vehicular networks must be able to maintain a constant connection and level of resilience. For example, wireless networks may encounter interference from natural landscapes (hills, mountains) and artificial data blockades such as tunnels (Spanos and Murray, 2004). In addition, a socio-technical perspective must indicate how future ubiquitous services will behave and perform in a way that allow road users the guarantee of optimal safety, navigation and Origin-Destination planning (Tuominen and Ahlqvist, 2010; Vlassenroot et al, 2010). Indicators must be developed to define how ITS services maintain user adoption. The performance definition should focus on standardisation and allow true network compatibility across the varying technologies both now and in the future. Network standards should be developed which are universally compatible with infrastructure, data types and transmissions (ITU-T, 2008; Highways Agency, 2010a; Tarte et al, 2010).

Four major areas of performance within ITS can be mapped within the context of environmental and socio-economic performance with each possessing their own specific attributes:

- Data Management and Information Complexity
- Sustainability
- Standardisation
- Adaptability

The proposed areas represent general performance categories of managing ITS within an inter-urban environment (although they could be applied to urban-based services.) Each area features its own performance index and the ITS performance management frameworks' route to optimisation (Figure 2.6) is expressed by the 'standards highway'. All performance areas should be linked via cause and effect variables. They represent the technical side of maintaining *continual service improvement* (ITS is built from an ICT/technical infrastructure therefore performance measures must be implemented objectively). They also aim to reinforce the governance of existing and future transport appraisal based upon governmental policy (Department of Energy and Climate Change, 2009a).

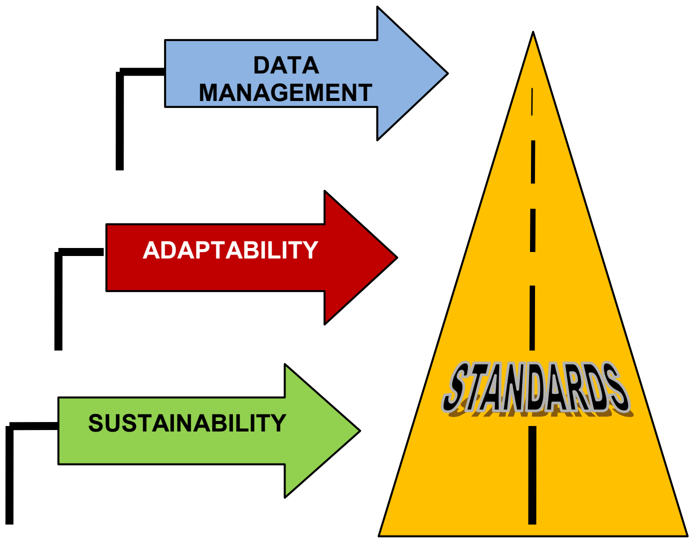

Figure 2.6: - Standardisation of ITS Socio-technical Performance Areas

The framework to be developed should be compatible with the UK governments (Department for Transport) and the European Commission's (EC) baseline targets and is the focus of the thesis. Because of the current issues surrounding climate change it is necessary that any current or future ITS based solution must be aligned with the targets of these bodies, in particular, the UK and Europe.

2.6 Summary

In this chapter, the appraisal of ITS performance has been evaluated from environmental and socio-economic perspectives. The framework required to be modular and designed with other evaluative conventional tools in order to retain familiarity with transport stakeholders, thus reducing the level of training required by practitioners in adopting the selected appraisal strategy. Estimating the performance of ITS is complex as it relies upon a number of actors including manufacturers, users of the system and the supporting legislation requirements such as carbon reduction targets. Methods that support the combination of varying data types from socio-economic and environmental perspectives as well as ICT usage in multiple geographical locations such as the data center needed to be selected where applicable. From the problem rationale undertaken in the previous section, Table 2.3 provides a summary of the key deficiencies in ITS evaluation frameworks and their proposed solution in relation to this research. Note that these deficiencies are also evident in urban-based ITS, therefore the findings of the thesis may also be applied to improve urban-based ITS evaluation approaches.

Chapter 3 outlines the research methodology based upon the problem rationale. The development of the proposed framework differed from conventional and ITS evaluation methods as it is required to be focused on the internal relationships of the physical infrastructure, the actors such as the vehicle, TCC, RCC as well as the mapping of technical, social and environmental standards. In conclusion, the framework needed to be designed as a fully integrated top-to-bottom evaluative tool for assessing service performance *between* the various actors rather than focusing on the direct benefits of the ITS system in both ex-ante and ex-post periods.

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

Table 2.3: - Deficiencies in ITS performance evaluation frameworks

"Recent R&D advancements in complexity, complex systems, and the intelligence sciences have provided us an opportunity to look into new methods of conducting intelligent traffic control and management from new perspectives, at the system level with new tools, and an integrated approach" (Wang, 2010).

Chapter 3 - Research Methodology

This chapter discusses the research methodology. The problem rationale from the previous chapter is used to define and select appropriate research methods. Methodological issues such as the format of the case study to be undertaken are defined and research techniques in relation to data collection are proposed. Each technique is evaluated as are the approaches adopted. The research methodology is part of a focused path to completion via several steps, leading to a critical review of environmental systems analysis tools in Chapter 4 and then the creation of a large case study with multiple embedded units of analysis in Chapter 5.

3.1 Introducing the EnvFUSION sustainability performance framework

This section discusses how the proposed problem rationale in Chapter 2 was used to define the research methodology for the thesis. The available methods are discussed in detail in the following chapters. The framework aimed to capture the inter-dependencies between performance criteria and the opinions of stakeholders in order to produce a prioritised performance result of ITS schemes in the present and future.

As discussed in Chapter 2, there is a need for an integrated sustainability framework for assessing the emissions, social and economic performance due to deficiencies in what limited ITS appraisal approaches currently exist. Referring to table 2.3 in more detail, the framework was developed based upon the weaknesses of current ITS evaluation procedures. The author has named the proposed framework as 'EnvFUSION' which has been designed as an internationally relevant, integrated assessment approach as part of a wider strategic performance management framework (Kolosz et al, 2012).

There has been no standardised accounting methodology for integrating emissions of the infrastructure, ICT and vehicles into the overall analysis as well as economic benefits gained from the offset of carbon. In order to resolve this, the results were combined using Attributional (for currently implemented ITS) and Consequential Lifecycle Assessment (cLCA for proposed ITS technologies) together with the priority setting and pair wise comparison of an Analytical Hierarchy Process (AHP).

Current transport appraisal frameworks only take into account certain gases such as CO_2 and therefore do not represent the complete potential of an ITS services effects on climate change. The Ecoinvent[1] database was used to determine emissions factors of materials using a Global Warming Potential (GWP) method with a fixed time horizon of 100 years (Lashof and Ahuja, 1990; Frischknecht et al, 2005; Frischknecht and Rebitzer, 2005).

Another weakness of ITS evaluation frameworks was that current indicators for example are biased towards economic benefits in that the output is monetary. The proposed solution was that each index value was weighted and given a normalised performance value so that the combination of criteria with unique

[1] Ecoinvent is an emissions inventory cataloguing different types of materials and their processes. See Frischknecht et al (2005) and Chapter 5, section 5.3.3 for more information.

weights can be consolidated through a holistic performance indicator. Dempster-Shafer theory (DST) was used in combination with AHP to form a prioritized Intelligent Transport Sustainability Index from sustainability criteria, using subjective quantitative probability assignment. The rationale for integrating AHP and DST was 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 prioritization by decision makers of various targets which aim to reflect socio-economic and environmental objectives. Different actors possess different and sometimes conflicting requirements in terms of performance which will affect their perspective of the ITS system. There are therefore advantages in deriving a method that can reflect both objective quantitative and subjective qualitative data. While the state of the traffic system under ITS is assessed using marginal data sets, certain elements of ITS are calculated in isolation and not all greenhouse gas emissions are taken into account. The EnvFUSION method allows a range of different scenarios to be modelled regardless of the configuration and scale of ITS services.

There is currently a Lack of reporting on how ITS schemes can assist in meeting national emission targets within the evaluation, therefore a distance-to-target method was created which could support input from multiple layers of decision making.

Current ITS frameworks only assess the services based upon a singular location rather than the whole system. The framework is focused at the macroscopic/strategic perspective defined as the level at which technologies cooperate as a system, with input from the microscopic level (such as evolutionary improvements in material production and resilience etc). A review of the methods described above and how they were selected is conducted in detail in Chapter 4. Finally, technical performance areas such as data management and adaptability are not cross referenced with environmental and socio-economic areas, therefore a strategic inter-scheme comparison matrix is created which aims to identify emissions and energy hotspots.

3.2 Methodological steps to developing the framework

This section defines the methodological stages that were followed in order to develop EnvFUSION. The proposed framework was developed through a variety of individual research steps which lead to an eventual case study of inter-urban ITS on a congested highway in the UK. The initial step was to perform a critical review of existing appraisal tools. The second step was to develop the ITS performance criteria through interviews, documents and historical records. The development of the study was based upon current and future (up to 2050) perspectives where the expected introduction of key ITS technologies would be explored. The third step was to conduct the case study on a stretch of highway that was prone to severe congestion but which also had ITS services currently implemented known as Active Traffic Management. The fourth step consisted of the design of an inter-scheme comparison matrix which could be used to correlate the data strategically from each set of performance criteria. The final step was the evaluation of EnvFUSION's main output to measure if the scenario criteria and performance management framework achieved its objectives. Methods included deductive reasoning on the proposed output to determine if the framework was valid and consistent with research objectives. Figure 3.1 over the next page illustrates the research lifecycle and accompanying methods.

3.2.1 Step 1: Review of sustainability decision methods

In order to determine which methods were appropriate for the framework, a critique of sustainability system analysis tools was conducted in order to determine their applicability for inter-urban performance estimation. This included conventional transport appraisal methods such as Cost-Benefit Analysis (CBA), Multi-criteria Analysis (MCA) and environmental tools such as Lifecycle Assessment (LCA). Each tool was evaluated using qualitative scoring based upon the expected contribution towards the EnvFUSION framework. Each tool used their own independent methods which were selected using subjective scoring depending on their relevance. The critical review is reported in Chapter 4. The review also highlighted procedures to reduce uncertainty when assessing inter-urban ITS. In addition, recent techniques to estimate the embedded emissions of ICT hardwareare illustrated. The Environmental modelling field is also explored to determine compatibility between each tools and their specific weights.

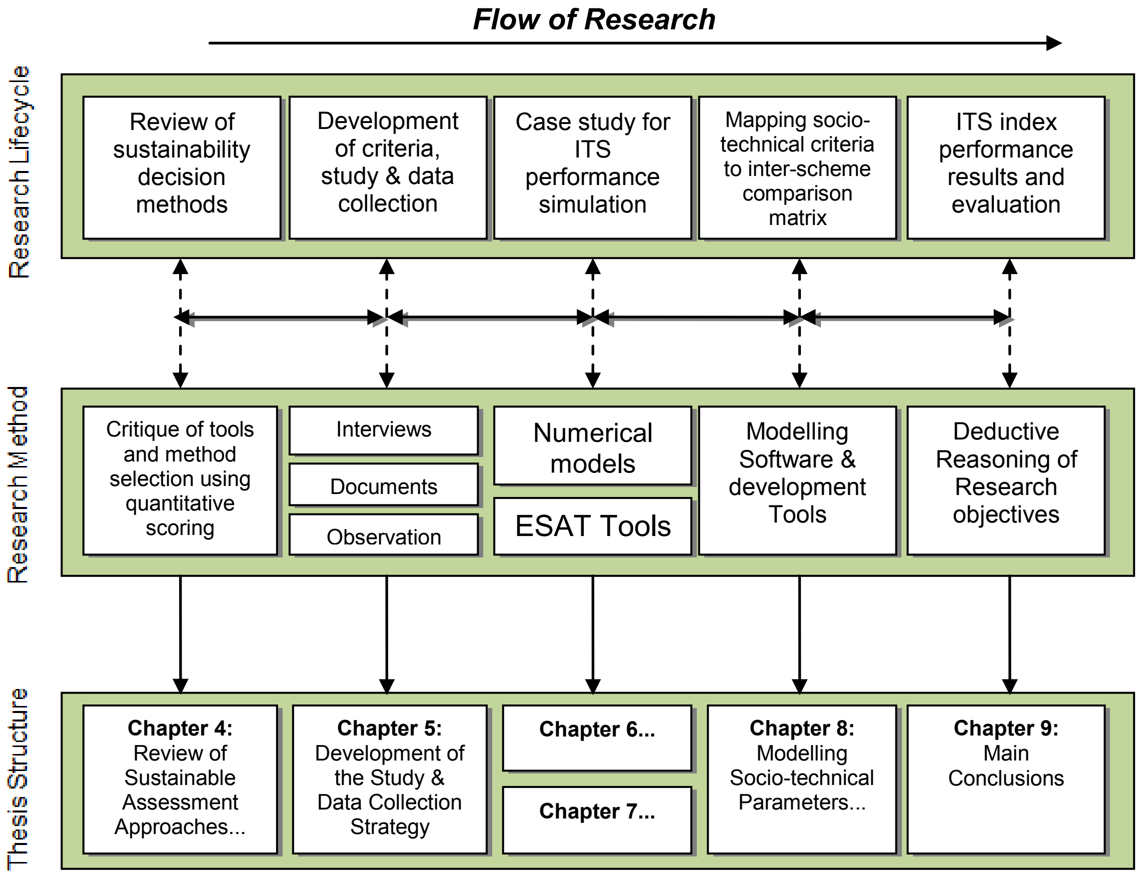

Figure 3.1: - Research Lifecycle and Methods

3.2.2 Step 2: Development of Criteria, Study and Data Collection

In order to understand the current configuration of technical systems used to control Active Traffic Management as well as the data flow of the existing transport infrastructure, a range of interviews were conducted with members of the highways agency and their up-stream suppliers. Interviews allowed the author to ascertain the viewpoints of the target individual in order to gain a rich pool of information relating to how the current road network operates in terms of technology, system requirements and future road mapping. According to Oates (2005), recording interviews allows the interviewer to concentrate on the process of the interview and they may find it easier compared to other research approaches such as questionnaires. This was avoided due to some interviewees feeling uncomfortable and therefore did not want their voice or themselves recorded. Keats (1999) and Yin (2009) discuss the benefits and drawbacks of interviews, stating that they are good at dealing with in-depth topics and providing a rich analysis. However, they can be misleading due to the focus on what the interviewees say rather than the reality of the question. To counteract this weakness, documents were also acquired where available to validate the information gained from the interviews. In the case of a standard semi-structure interview the questions should be referenced, although the majority of the communication took place over the telephone with the up-stream suppliers. Two face-to-face interviews were conducted with members of staff at the Highways Agency's regional traffic control centre (TCC) in Wakefield, West Yorkshire. The first interview was conducted with the team manager responsible for the management of the TCC while the second was conducted with the data center operator. Between February and April (2012) four sets of telephone Interviews were conducted with the Highways Agencies up-stream suppliers in order to determine the weighting and material usage of the road-side infrastructure. In addition, another interview was conducted with one of the strategic managers of the HA, where data was collected to determine criteria for EnvFUSION's higher function, an inter-scheme comparison matrix. These interviews were held in confidence, therefore they do not appear in the thesis.

A Systematic observation of key services such as the data center was conducted to gain an overview of energy efficiency and levels of aggregation should data prove to be difficult to obtain. In order to assess the data centers' energy efficiency as well as the general running of traffic control centre ATM procedures during severe congestion, observation techniques were utilised. Observation plays a key role in analysing ICT systems. According to the literature (Dawson, 2000; Oates, 2005; Yin, 2009) there are mainly two different types of observation: *Systematic* and *participant.* Systematic observation tends to focus on processes that have been pre-arranged in advance for monitoring. While *participant* observation is where the researcher will take part in the task for study. In terms of this research there is no intervention required as the analysis involved monitoring of the energy consumption of the data center. Therefore *systematic* observation was utilised for the analysis phase of the project. Observation allows a large amount of quantitative data to be obtained very quickly. This is due to the data being pre-coded hence it is ready for analysis. Oates suggests that performing critical observation allows unseen processes to be extracted and a richer picture to be obtained of the organisation. Unlike interviews, the real processes can be defined rather than rely on an individual saying what they are going to do. However, depending on the method of observation, it was argued that only the behaviour can be studied rather than the intentions, meanings or reasons. It is also difficult to provide feedback to people that have been observed which means techniques such as *covert observation* may have questionable ethics. Finally, Oates (2005) discusses simplification drawbacks, stating observation assumes that chaotic behaviour can be broken down into various sub-tasks which can be categorised. Therefore observational techniques may over-simplify a particular situation or in terms of ICT, a visual display of the system is not usually interpreted simply by reading indicators.

Documents relating to the assessment of the selected highway were collected from the highways agency and literature. Oates (2005) and Seale et al (2004) refer to the use of documents as 'hard' evidence and they can be utilised within any of the research strategies for research including design and creation, surveys, case studies, ethnographies, experiments and action research. Seale et al (2004) refer to this as a *themes analysis* in that a variety of data is extracted to benefit the focus of the topic which allows documents to be accumulated quickly, especially if they are low-level and non-confidential to other parties. Business documents were readily available from the Highways Agency as they were situated within the public domain and they are permanent and can easily be found. However, to determine the carbon accounting framework, an external organisation was contacted in order to retrieve the necessary data. This allowed the researcher to carefully scrutinize them for data extraction and relevance without bias. Pre-made templates can be accessed freely without confidentiality risks however, they must be evaluated carefully and only the data that is relevant should be extracted. Access to other documents such as Interim advice were only temporary and care had to be taken to check for possible updates or removal. Although some documents may be expensive which means other research approaches may have to be used in order to gain the information required, this was not the case in terms of data collection. Lastly, categorisation methods may change or carry a certain time frame meaning that documents may become inaccurate very quickly. Once again, this was avoided.

The data collection strategy and the development of the studies was carried out in Chapter 5. Scenario criteria was developed in order to test the *boundaries* and *fault tolerance* of the framework in a practical real-world example. These scenarios were developed using varying criteria that would allow EnvFUSION to produce different results based upon external or exogenous data.

3.2.3 Step 3: Case Study for ITS Performance Simulation

The design of the study, data collection procedure and criteria led to the selection of a stretch of UK highway. The highway selected was based upon several criteria. The target highway should be situated in a location where there is severe traffic congestion and will already have some form of ITS service in operation so that historical data is available to validate its current performance. As the HA has recently implemented ATM on the M42 at junctions 3a to 7, it appeared during the planning stage that this was the most prudent choice to apply the sustainability performance framework. The case study focuses on assessing current ITS performance which includes assessing the emissions and socio-economic performance of ATM and also the impact of future inter-urban technologies up to 2050. It was decided that a large single case study would be suitable to evaluate EnvFUSION. The selected tools, methods and weights from the review of environmental models in Chapter 4 would be used to estimate the performance of current and future inter-urban ITS. It is important to note that the testing of the framework was carried out through sensitivity analysis which was applied to the output in order to test the robustness of the framework. This was described in more detail in Chapter 6.

3.2.4 Step 4: Mapping Socio-technical criteria to the inter-scheme comparison matrix

In addition to EnvFUSION, several other performance indicators were defined in Chapter 2. These represent socio-technical criteria and in order to consolidate the data from each of the performance areas, an inter-scheme comparison matrix was developed in Chapter 8. This included quantitative values and weights in determining environmental, social and economic benefits. It was necessary to define the inter-performance relationships through a set of analytical models consisting of a variety of feedback loops. The purpose of this is to determine dependencies so that cause and effect relationships can be identified. It is believed that the identification of these relationships will increase the accuracy of the performance management framework. However, it was important to clarify how the attributes between the different criteria behaved and the attributes general format (quantitative or qualitative). In addition, each performance indicator would behave differently, therefore the models that were developed were customised individually for each performance areas specific attributes. System dynamics for example, allows complex real-world problems to be understood via feedback loops with positive and negative polarities. The main aim of system dynamics was to discover the unanticipated side effects of policy resistance, unintended consequences and counterintuitive behaviour of systems. In other words, when attempting to solve a problem, hidden reactions may provoke this problem further. Newman-Askins et al (2003) highlights that cause and effect relationships in ITS projects are more complex than conventional projects. The impacts of the interactions and synergy between components are far more significant than the effects of any individual component.

Understanding the dynamics and behaviour of individual ITS attributes (including actors and data types) may lead to a better understanding of maintaining performance in future low-carbon transport networks. Stermans[2] (2000) system dynamics model was selected to display the cause and effect relationships using a combination of feedback loops as well as stock and flow models. A thorough breakdown of the relationships between performance indicators was conducted in Chapter 8.

3.2.5 Step 5: ITS Index Performance Results and Final Report

In the final step of the research methodology, the performance results from the ITS sustainability index is evaluated. All research objectives are then cross referenced with the evidence in the report to ensure they have been achieved. In addition, the proposed solutions within the research are cross-checked against some of the deficiencies of current frameworks to demonstrate the areas where improvements have been made

3.3 Case Study Research Design

This section discusses the methodology for the case study which includes the development of the case study method and an evaluation of case study designs.

3.3.1 Case Study Method and Development

In order to test the EnvFUSION framework, it was decided that a case study approach would be selected. Eisenhardt (1989) and Gerring (2004) refer to a case study as a research strategy which focuses on understanding dynamics within single settings (single case study), or an intensive study of multiple units with its main aim to generalise across a larger set of embedded units (multiple case study) divided across multiple layers of analysis. Robson (2002) highlights the case study as:

> *"the development of detailed, intensive knowledge about a single case, or a small number of related cases".*

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[2] As a counter argument to using the System Dynamics method, Sterman (2000) argued that technologists attempting to pin the future of the road network on technology may find this approach futile. This is because as the road network increases in efficiency so will the quantity of vehicles on the road. This argument however has proven unfounded due to vehicle efficiency also increasing.

The most recent definition is reinforced by Yin (2009) who describes the case study as an empirical enquiry that investigates a contemporary phenomenon within its real-life context, particularly when the boundaries between phenomenon and context are not clearly evident. In addition, a case study approach is appropriate in answering the *'how'* and *'why'* type of questions focusing on contemporary events. This view is also supported by Robson (2002) who maintains that:

> *"the case study approach has considerable ability to generate answers to the question 'why'"*

Case studies can be classified as exploratory, descriptive or explanatory (Schell, 1992). Yin (2009) maintains that there is no exclusivity with regard to these classifications and that they can be combined in one pluralistic research approach. Both exploratory and illustrative aspects may be combined in one case study with the accent being on the 'typical'. Also, cases can be 'typical' or 'selective'. The selective case study focuses on particular issues or aspects of behaviour to provide a better understanding of the phenomena, and that these case studies answer the *'how'* and *'why'* questions leading to explanatory evaluation. Schell (1992) discusses explanatory research and focusing on particular issues using a selective case study approach. Data from other forms of research, including surveys and statistics can be corroborated and illustrated through richly detailed and precise accounts. Schell also maintains that the value of the case study can be measured by generalization to other situations. On this basis, it would seem appropriate to undertake a selective approach to the case study research in terms of emphasizing the relationships between sustainable transport and ICT indicators. Conducting a generalization against existing environmental performance indicators and company documents where appropriate, emphasized the carbon reduction targets of the UK in the current, short-term and long term.

3.3.2 Evaluation of Case Study Designs

According to Yin (2009) and Schell (1992) multiple case design strategies feature significant advantages and disadvantages compared to the classic single case design. Single case studies tend to focus on typical, critical or revelatory cases and tend to be analogous to single experiments, while multiple cases may be used to replicate or to compare and contrast. The adoption of a multiple case study approach improves theory building, and by comparing various cases the researcher is in a stronger position to establish the circumstances in which a theory will or will not hold (Eisenhardt, 1989; Yin, 2009). The evidence from multiple case studies tends to be more persuasive and cogent. The study is therefore more robust compared to studies in the classic format. However, the approach and method of a single case study cannot be replicated within a multiple case framework.

> *"The unusual or rare case, the critical case and the revelatory case are all likely to involve only single cases, by definition. Moreover, the conduct of a multiple-case study can require extensive resources and time beyond the means of a single student or independent research investigator". (Yin, 2009)*

In the context of the research proposed in this thesis, the unusual, critical or rare case can be applied to a single stretch of highway which encounters extreme variability in traffic flow. For example, the M42 highway experiences extreme variances in traffic due to a number of key points. First, a combination of long distance and local traffic makes the M42 section between J3a and J7 one of the busiest motorways in the UK; with the total daily traffic varying between 50,000 and 75,000 vehicles per direction (Sultan, 2009). Secondly, the three junctions located within the ATM section allow for local traffic to use part of the sector to reach their destinations. This is particularly true of J6, which provides the main link between Birmingham International Airport and the motorway network - as well as being the main junction allowing access to the National Exhibition Centre (NEC). Finally, the NEC hosts various large scale events which will cause fluctuations within the local traffic area.

Dyer Jr and Alan (1991) argue that a multiple case study approach may involve the researcher paying less attention to the specific context and more towards contrasting across the case study sample. They also state that in order to forge comparisons, the researcher needs to develop an explicit focus at the outset. They argue that the adoption of a more open-ended approach to the multiple case study approach could be advantageous in many instances. However, as the implementation of ATM was only carried out on the M42 at the time the research was conducted and due to the complexities in data collection and level of focus, the multiple case study approach was considered unfeasible for this research. Typically, large single studies contain multiple embedded units of analysis. Figure 3.2 below sets into context the characteristics of each case study design in a 2x2 matrix as applied to this research. Yin (2009) argues that there are two specific case study designs that are configured in a holistic (single unit of analysis) or embedded (multiple units of analysis) approach (bottom left cell/2x1).

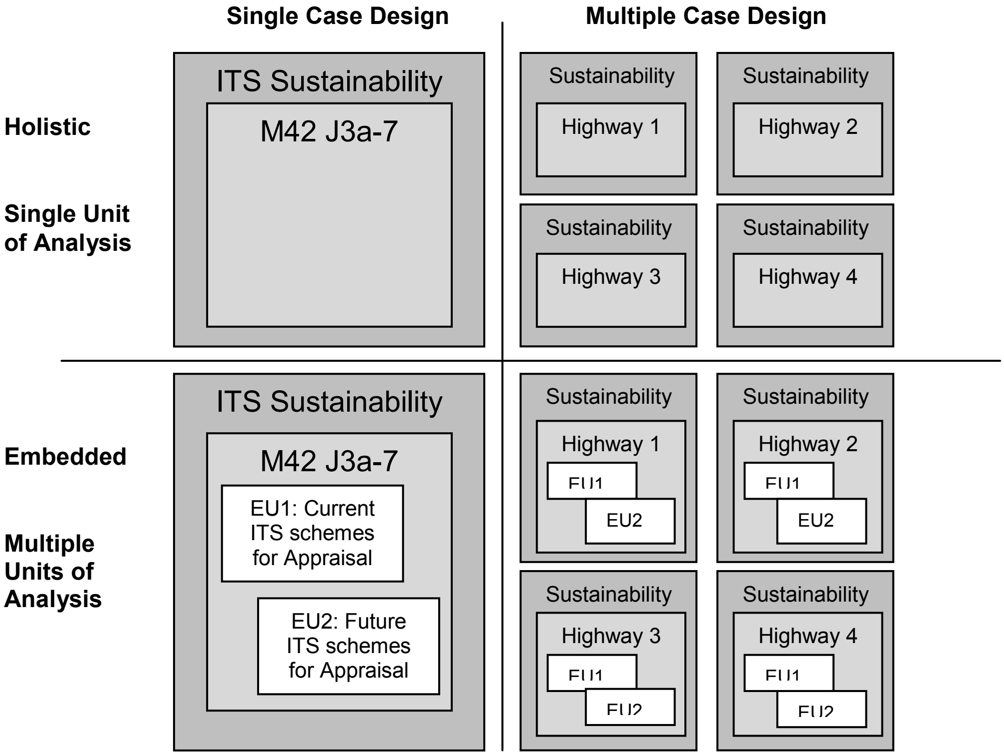

Figure 3.2: - Case Study Designs within the context of the research (Source: adapted from Yin, 2009)

During the planning phase it was thought that the socio-technical indicators (i.e.. Adaptability, Data management etc) would have their own data collection phase and would also be applied to the selected highway. However, due to timing constraints this was not possible. Also, it was thought that if other highways featured similar ITS services at the time of the investigation, a multiple case study approach could be applied as shown in the lower right matrix in Figure 3.2. Unfortunately, only the M42 featured ATM at that time.[3] The case study selected for this research project can be described as a single case design with multiple embedded units of analysis. Two embedded units of analysis were designed within the single-case format. For each unit of analysis, an appraisal of current and anticipated ITS technologies was carried out. A set of specific scenarios formed the embedded units of analysis generalized within each study. Figure 3.3 illustrates the varying stages of the single case study method adopted in the thesis.

3 See Chapter 9 for future work

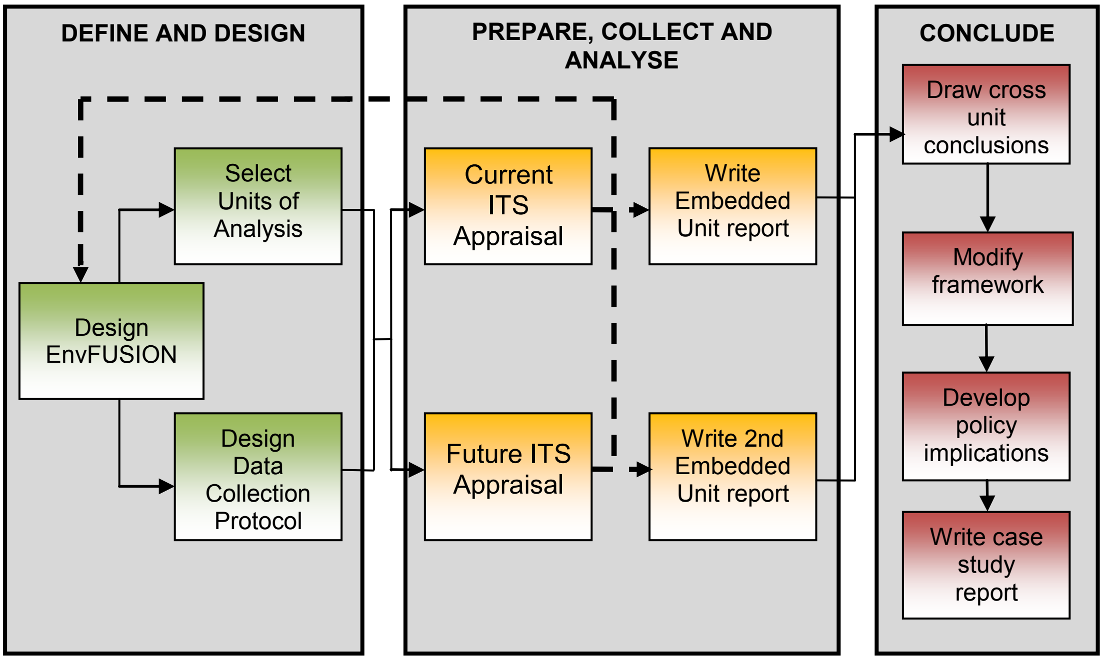

Figure 3.3: - Single case study method with multiple units of analysis (Source: adapted from Yin, 2009)

The first stage step in the design of the method is the development of the proposed theory. EnvFUSION was developed in order to improve the weaknesses of sustainable ITS appraisal strategies (Chapter 2, Table 2.2). The case study is then used to test the new method although it should be noted that it is independent of the exact case used to test it. The scenarios were selected and the design of the data collection protocol was carried out. For this research, the framework was developed from the bottom up and developed from a selection of existing indicators. These data sets were processed via a number of environmental assessment tools to form an index of embedded criteria featuring weighted variables. The proposed EnvFUSION framework was then designed based upon a collection of ESAT tools where a review of the selected tools is conducted in Chapter 4. This combined approach would allow traditional deficiencies of each tool as a standalone approach to be reduced. A method which could be capable of prioritising ICT and transport parameters into a consolidated data set through high level data fusion was used. The use of generic criteria would then be applied to both ICT and transport data categories. The LCA is used to assess and predict the future operational performance of the chosen ITS service type that may be introduced or operated in the future. The two scenarios are undertaken and the results of the evaluation of the case studies is presented'. The final stage relates to the conclusion of the study where cross unit comparisons are then undertaken. At this point, the theory is modified to take into account the results of the study. Policy implications are highlighted and the final report is undertaken together with appropriate conclusions.

3.4 Methodological Issues

This section discusses the methodological issues and how they were tackled within the context of this research.

3.4.1 Research Scope

The research scope aimed to be designed around an ITS scheme comprised of three main focal areas, the road-side infrastructure, the data center situated within the regional traffic control centre and the vehicles that traverse the highway. During the planning phase of the study, it was also deemed plausible to assess the energy consumption of future vehicular networks although this depended on whether historical test data was available. Figure 3.4 illustrates the environmental scope of the focal objects at the system level of an ITS scheme.

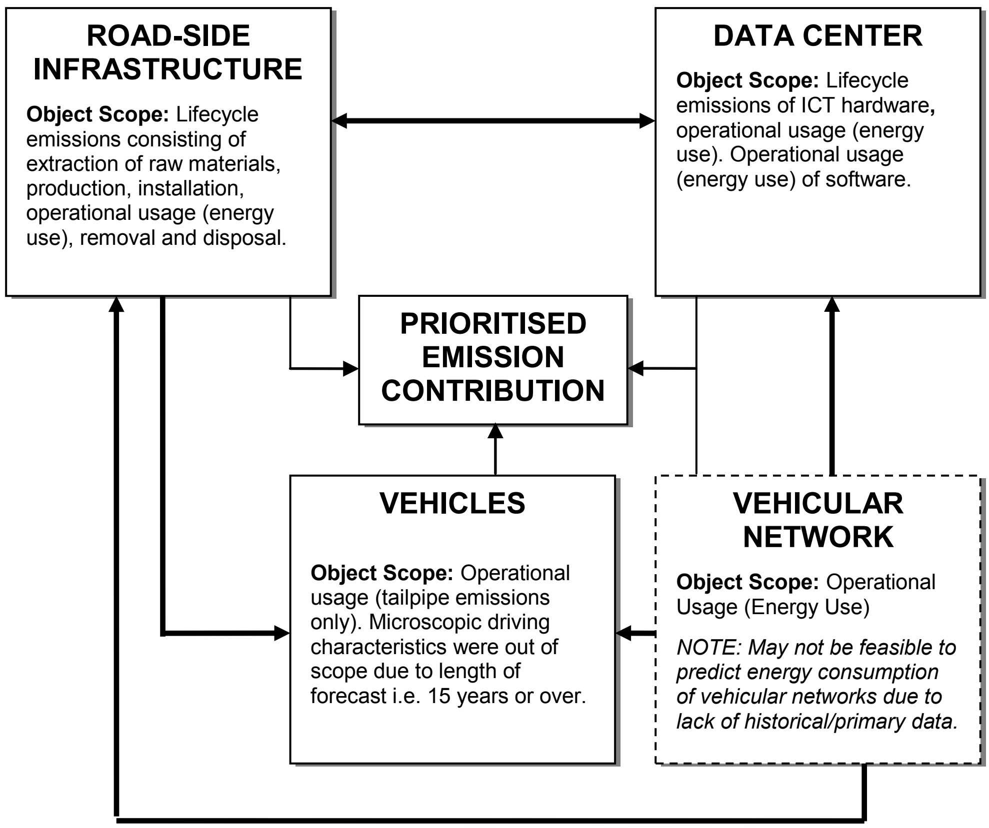

Figure 3.4: - Environmental scope within an ITS system

This level of scope was designed to improve the weakness of appraisal frameworks that focus solely on the stretch of road.

3.4.2 Road-side Infrastructure

The road-side infrastructure belongs to a larger system architecture which the HA (2010b) have been operating for the past 40 years. It has evolved over a need to maintain support of the growing complexity of the road network. The network consists of thousands of individual pieces of infrastructure (variable message signs, CCTV, emergency phones etc). The network is connected via a series of fibre optic and copper based cables which transmit voice and data signals between the infrastructure and regional control centres. Cables required replacing and there was usually not enough extra capacity to build new data connections. In 1998, the role of the HA was refocused in the role of network operator via the 1998 white paper *A New Deal for Transport: Better for Everyone* and the associated roads review a *New Deal for Trunk Roads in England (1998).* A new directive was added to the HA:

> *"To contribute to sustainable development by maintaining, operating and improving the trunk road network".*

The National Road Telecommunication Service (NRTS) project was conceived soon after in order to provide a national approach to the development of the current and future telecommunications framework and the services it supplies. NRTS is designed to manage data between the infrastructure and the regional control centres and Figure 3.5 illustrates the basic concept of the project.

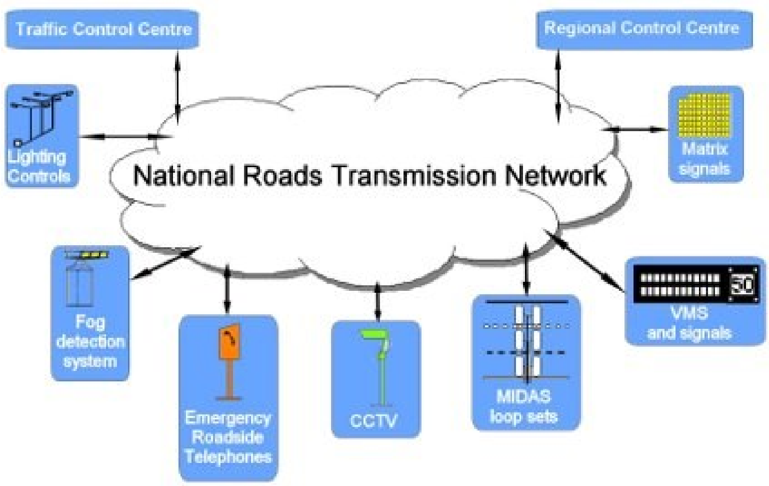

Figure 3.5: - National Roads Transmission Network with Actors (Source: Highways Agency, 2010b)

NRTS can be defined as a national ITS system based at the National Traffic Control Centre in Birmingham. Video images are sent over fibre-optic cables to form a switched video network. The fibre-optic system was deployed with *Guardian-Lite 3700* controllers, which allow IP Ethernet and (full bandwidth) uncompressed video signals to be sent at the same time, made (and invented) by AMG Systems of Biggleswade. The system uses a dual fibre cable. The system is resilient because, using the IP protocol, it can re-route signals if cables are damaged. GeneSYS possesses total responsibility for the telecommunications network, however the actual road side devices remain the property of the DfT.

> *"GeneSYS are responsible for providing a resilient and reliable service and for monitoring the performance of the telecommunications services" (Highways Agency, 2010b).*

GeneSYS are required to perform the following operations: -

- Provide telecommunications services on a national basis
- Co-ordinate and manage the planning of telecommunications services
- Maintain existing and future telecommunications services
- Upgrade and extend telecommunications services to enable the Agency to expand the network
- Develop new types of services required by new initiatives such as Active Traffic Management
- Facilitate and manage any commercial third party opportunities, for example, generating revenue by using spare capacity in the fibre optic cable network
- Provide web based information
- Provide an aerial site service
- Provide design and consultancy services

The individual connections are known as a Service Type Instance (STI). Each STI is designed to connect with a certain road-side device. GeneSYS took over 15,000 STI's in the beginning and that number has almost certainly grown over the past 5 years. The major advantage of NRTS is its modular ability of STI's and its space for expansion as the services become more efficient. They are also responsible for installing, repairing and removing STI connections (Highways Agency, 2010b). The network is therefore already prepared for the forthcoming generation of ITS as and when the technology and supporting infrastructure is available. This has allowed a new form of ITS known as ATM to be implemented on the road network, however, the embedded emissions of such systems are unknown at this time and vary on a link-by-link basis.

In Chapter 2, Table 2.2, it was acknowledged that several weaknesses existed in attempting to evaluate this system in terms of its road-side infrastructure. Firstly, not all greenhouse gas emissions were taken into account with most carbon accounting frameworks being focused on CO_2 emissions. For example, the HA's framework of ATM only focuses on KG of CO_2 of embodied material as opposed to taking into account all GHG emissions in CO_2 equivalency. There is also a large degree of ambiguity in the production process in terms of the material grade, recycling ratios and energy usage. There is also some ambiguity in quantifying the emissions of ITS equipment connected to the gantries as they are identified as a combined piece of equipment. By including all possible emissions in the lifecycle of the infrastructure, it is possible to more accurately predict the total contribution of its global warming potential. This includes the total lifecycle of all materials used in the construction of the ITS infrastructure on the road as well as the operational energy consumption. As there is a large degree of uncertainty, data may be missing or inaccurate, particularly when assessing the full lifecycle of emissions.

3.4.3 Data Center/Traffic Control Centre

As discussed above there are a variety of different data types or STI's that are managed by traffic control centres through the NRTS system. Data must be sorted and verified in order for them to be of any use. However, in future ITS systems this data must be processed and relayed instantly (real-time) in order to maintain a safety critical application. The main problem according to Lochert et al (2008) is that current wireless networks have a limited data bandwidth as well as minimal initial deployment. According to Bohm and Jonsson (2009) data is gathered from surrounding vehicles or roadside units (RSU). They define real-time data as deadline-dependant data that must be delivered to its destination for the application to be successful.

As illustrated in Figure 3.4, the framework aimed to capture the total emissions from the hardware and software level if possible. Estimating the energy consumption of software for example is challenging due to a lack of sufficient metrics and measuring systems (Shah et al, 2009; Cappiello et al, 2011). Ideally, the hardware that is designed to accommodate the data links between the traffic control centre and the road-side infrastructure should be subject to a full lifecycle assessment, although again this may not be possible due to the high degree of variability in system specifications and non standard emission data sets (Krishnan et al, 2008; Shah et al, 2009). Aggregating the level of contribution at the software level may also encounter issues due to a lack of metrics and if this was the case then the level of aggregation was aimed at the hardware level.

In terms of socio-technical data collection, estimating the data types and efficiency of vehicular networks however proved difficult due to differences between some Driver Assistance Systems or DAS (Delot et al, 2010). Navigation for example which uses GPS as the transmission device only uses static data (points of interest for example) which are stored within a memory card. Inter-vehicle Communications (IVC) aim to utilise a greater deal of dynamic data that are event based and rely on location and time. Dynamic data is also screened to ensure data is valid and verified by an official source. Wireless access in a vehicular environment (WAVE) can be classified as a primary technology in order to realise safety-critical apps. Current WAVE standards include IEEE 802.11p which is an adaption of the wireless LAN standard. Delot et al (2010) and Mehani et al (2009) refers to the information exchanges in vehicular networks as dynamic since each driver requires different types of useful data using short and efficient interactions. Due to the ad-hoc nature of these networks a new information dissemination framework is required to sort and distribute useful data to the users of the network at the right time. Naumov and Gross (2007) proposed connectivity aware routing in order to maintain a connection via finding connected paths along the route the driver takes. This would enable a more stable VANET.

Wireless networks for vehicle communications have a short range (100 metres). The data bandwidth will be in the region of Mbps (Megabytes per second). While it is possible to use wide-range networks (mobile phones - GPRS/UMTS etc) the lower bandwidth (usually 100 Kbps) may not be adequate. Information is sent and received by vehicles automatically, data will be passed between neighbours as they pass by on the opposite side of the road or carriageway. Data will also be passed between vehicles in front and behind to share relevant information such as speed for that particular section of road. This sort of network will offer very interesting data management challenges since the data is dependent on the 'handshake' protocol of nearby vehicles (Luis et al, 2010).It is apparent from the discussion that socio-technical data must be developed with regard to these assumptions in order to determine the performance of future services depending upon the configuration of the ITS system.

3.4.4 Vehicle Emission Modelling Issues

Modelling the emissions of vehicles can be undertaken via several different focal levels. According to Ferreira and d'Orey (2012), emission models can broadly be categorized into Macroscopic, Mesoscopic, and Microscopic models. The macroscopic approach which is based upon average travel speed has been the most common methodology used for estimating vehicle emissions (Int Panis et al, 2006). In Europe, for example, most inventories of exhaust emissions at the fleet level or for a city as a whole are still calculated according to the COPERT methodology developed from the European MEET project (EC, 1999). These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions. An important drawback of this methodology is that it calculates emissions per KM for vehicle trajectories using primarily the average speed. Although the overall trip speed is an important factor influencing emissions, instantaneous speed fluctuation plays a greater part. For the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each resulting in very different fuel consumption and emission levels (Smit et al, 2010; Ferreira and d'Orey, 2012).For the compilation of emission inventories of large areas and over long time periods, this microscopic effect may be ignored and the results from the macroscopic models may give reasonably good estimates. In relation to estimating ITS service performance over a longer time period this appeared to be the most suitable option as microscopic accuracy becomes less important over a long term forecast and may give a more accurate estimate.

Mesoscopic models taking traffic dynamics partially into account by partitioning the traffic situations in several classes have been less widely used. More sophisticated hybrid approaches such as ARTEMIS are still in their infancy (André, 2004). Mesoscopic models use more disaggregate trip variables, such as the average speed, the number of stops, and stopped delay, to estimate a vehicle's emission rates on a link-by-link basis. Some regression models that were developed were found to predict fuel consumption and emission rates of HC, CO, and NOx to within 88%–90% of instantaneous microscopic emission estimates (Ding and Rakha, 2002).

Microscopic emission models overcome some of the limitations of large-scale macroscopic models mainly by considering individual vehicles dynamics and their interactions. Emissions and fuel consumption are estimated based on instantaneous individual vehicle variables that can frequently be obtained (e.g., second by second) from a microscopic traffic simulator or another alternative source (e.g., the Global Positioning System (GPS) data logger). Commonly, these parameters are divided into the following two categories; vehicle parameters and traffic/road parameters. Vehicle parameters include, among others, vehicle mass, fuel type, engine displacement, and vehicle class. On the other hand, network parameters (traffic and road conditions) account for instantaneous vehicle kinematics (e.g., speed or acceleration), aggregated variables (e.g., the time spent in the acceleration mode), or road characteristics (e.g., road grade). Because microscopic emission and fuel consumption models have higher temporal precision and better capture the effects of vehicle dynamics/interactions, they are better suited to evaluate the environmental gains derived from an ITS measure, such as the VTL system. Several microscopic models have been proposed by the scientific community. These models can be classified into emission maps (speed/acceleration lookup tables), purely statistical models, and load-based models (Cappiello et al, 2002). Major contributions in this field were given by Akcelik et al (2003), Barth et al (1997) with the Comprehensive Modal Emission Model (CMEM), Ahn et al. (2002), and Cappiello et al (2002) with the Emissions From Traffic (EMIT) model. It was decided early on that these models would be out of scope when assessing the advantages of the ITS technology due to the length of the forecasting period used in this research.

Several models that focus on the macroscopic and Mesoscopic level seemed applicable. The UK's National Transport Model (NTM) for instance uses a combination of ARTEMIS and COPERT IV emission factors. Generally, there was a very good agreement between the shapes of the emission curves in the NAEI and the various models tested, but the results varied with vehicle category and pollutant (Boulter et al, 2009). Rigorous testing was performed where available in an attempt to improve the results in several vehicle categories leading to the conclusion that the current UK emission factors should not be changed but improvements using the models above were made. It is this combination of models that were used for this research project.

3.4.5 Forecasting issues in ITS technologies

The basic approaches to forecasting include regression and time series methods which aim to make predictions about likely future events. It is a useful form of research in that it attempts to cope with the rapid changes that are taking place in ITS and predict the impacts of these changes on individuals, organisations or society. However, it is a method that is fraught with difficulties relating to the complexity of real world events, the arbitrary nature of future changes and the lack of knowledge about the future. Researchers cannot build true visions of the future, but only scenarios of possible futures and so impacts under these possible conditions. The performance of regression analysis methods in practice depends on the form of the data generating process, and how it relates to the regression approach being used. Since the true form of the data-generating process is generally not known, regression analysis often depends to some extent on making assumptions about this process. This is a key issue within the ITS field as in terms of emissions reduction, energy requirements, safety and cost. there is a limited amount of historical data through real-world trials available. Assumptions in this research must be carefully formulated or there is a risk that the forecast the past data is built on may be inaccurate to the point that it becomes invalid. The study area that was to be selected was chosen based upon the quality and availability of historical data

Some uncertainty exists in terms of the future hardware configuration. This depends upon the approach that will be taken by the road network operator and their appropriate technological roadmap. It is acknowledged that the future network within Inter-urban ITS involves four different modes (Fuchs and Bankosegger, 2009), the prediction of the future system must therefore be carried out with care. Traffic Control Centres (TCC) regulate the control of traffic and will also act as a central repository for information. Within the field of ITS, TCC's may be responsible for processing information from different sources in order to manage the traffic network more efficiently. Each mode can be used in conjunction with another. From a System Dynamics approach these communication modes have been categorised based upon the possible system types of Sterman's (2000) pioneering work on system dynamics. According to Sterman (2000), system dynamics modelling generally follows a 5 stage iterative process where the problem is defined (Boundary Selection). A dynamic hypothesis is generated from the problem which is then formulated using the modelling diagrams. The model is then tested using existing variables and expected results of dynamic behaviour. A policy is then formulated and evaluation of the system is displayed. The following list represents the possible types of communications as proposed within the current CVIS project. The system configuration based upon a system dynamics method is in brackets.

- V2V: Vehicle-to-Vehicle (Reinforced, Closed-Loop, Endogenous)
- V2I/R: Infrastructure/Roadside-to-Vehicle (Reinforced, Closed-Loop, Endogenous)
- V2C Vehicle-to-Control Centre (Exogenous, Open System)
- V2X Vehicle-to-Nomadic Devices (Exogenous, Open System)

The V2X designation implies that this type of services will also be equipped to maintain a connection to the network (even though the driver has left the vehicle) via a mobile device, although this is considered to be public access and will typically involve integration via some form of social network service.

Gil-Castineira et al (2009a) discuss a revolution in Dedicated Short Range Communication (DSRC). DSRC is a selection of one-way, two-way short to medium wireless communication channels that are designed specifically for vehicular use. Protocols and standards are designed to use these specific channels. DSRC can be referred to as a form of Telematic as it is used to understand the interactions of technology to provide services which incorporates sensors wireless devices, vehicle tracking and on-line navigation as well as vehicle operators and road network managers. Figure 3.6 illustrates these varying communication types possible within an ITS service.

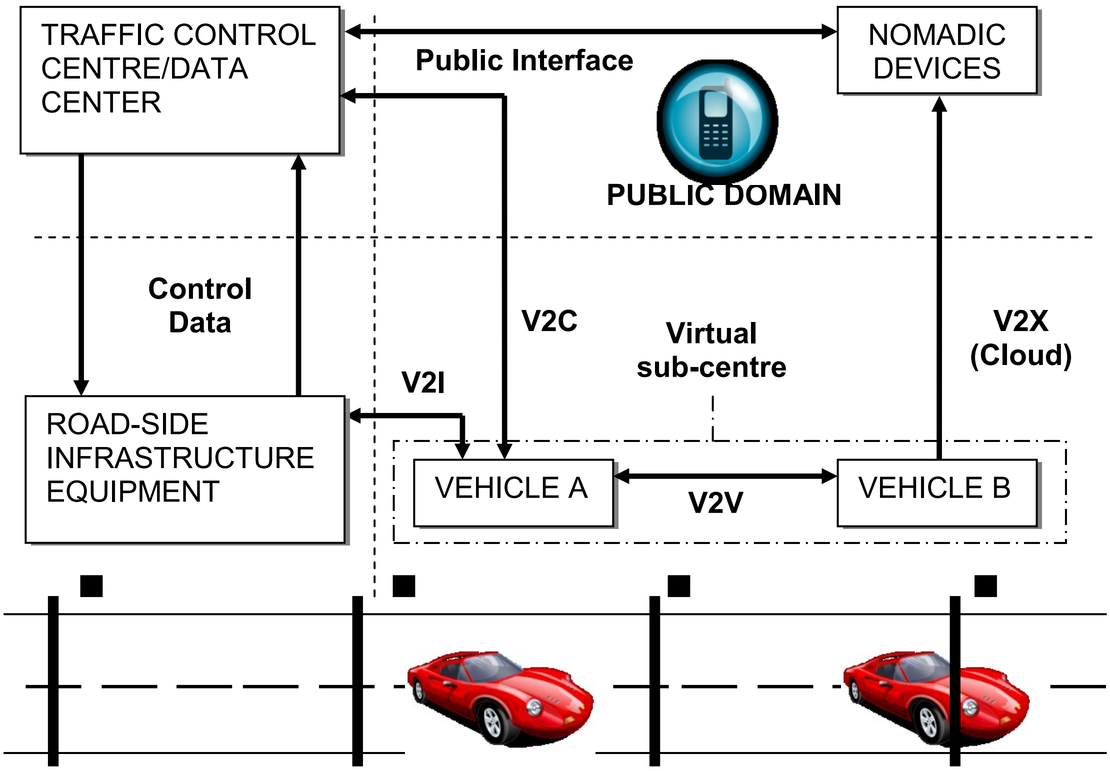

Figure 3.6: - Communication modes of an ITS System

It is important to note according to Ammoun and Nashashibi (2010) that current communications standards have not been tested within this environment neither have communications services been proposed. In one future scenario it may be possible to extend the National Road Telecommunications services to accommodate the latest and future advances within the communications research domain.

V2V is a form of communication within the Vehicular Network field. The vehicle sends data to other vehicles which can be used to manage safety and inform other road users of oncoming traffic as well as the current capacity of the traffic network (Bell, 2006a; Boukerche et al, 2008; Fuchs and Bankosegger, 2009; Hamouda et al, 2009). This form of communication is one of the main topics for debate within the intelligent transport literature and also carries the most uncertainty. For example, it is assumed that V2V communication will be able to operate independently of other infrastructure. This form of communications architecture is looking increasingly feasible from a standpoint of security (Weiß, 2011; Kaur and Singh, 2012), the general consensus is that some form of infrastructure will still be required on the road-side to monitor the network. This is because the vehicles are in a constant state of movement. It would prove impossible for a vehicle to possess all data containing all regions hence one approach has been to introduce a tagging system where a vehicle that comes into contact with another vehicle is sent a message about the local area within that current timeframe. In addition, a sifting method would need to be installed onboard the vehicle in order to remove data noise, to verify that the data is true and to enforce secure communication. This method would prove more advantageous than having to verify traffic data that is unsuitable due to a different highway or location being assessed for example. When forecasting future ITS services in this research, these assumptions must be taken into account. The advantages of the V2V communication system provides notification on hazards and collision avoidance between vehicles (Torrent-Moreno et al, 2009a; Santa et al, 2010). However, according to Rezaei (2010) tracking vehicles using wireless communications will be a tough task due to the vast differences of location and speed of the vehicles. However Mincheva (2009) refers to handling instances of data in a virtual sub-centre (VSC) as illustrated in Figure 3.6. The VSC will be able to manage and distribute data depending on the time and location the connection was made.

> *"VSC is a subset of a VANET but not necessarily the whole VANET. Only vehicles that are involved in the same traffic situation and have the same transportation need of sharing traffic related information are connected with VSC functions" (Mincheva, 2009).*

Hence, a group of vehicles in a V2V connection that is composed on a network protocol level is known as a VANET cluster. They can communicate but only within an instance relative to a current timeframe at that particular moment as well as vehicles that are diving in the same direction. A VSC is maintained via a knowledge sharing community or vehicular event sharing as discussed by Delot et al (2010) earlier. All the vehicles provide their knowledge into their VSC network in order to make systems that are independent work together. Data redundancy is therefore approved in this situation since any vehicle can disconnect from the network as they traverse the road network (changing roads etc). They are also operated in a decentralised manner but possess a common transport interest (Mincheva, 2009). Each vehicle also receives and acts upon this data independently taking in factors that are unique to the vehicles status. When travelling alone, vehicles may use other forms of communication to remain updated on current situations For example, a V2C connection will allow users to maintain updated as well as basic information about the surrounding area or region. The average life-time of a VSC instance is short (due to communication ranges etc) and a plug and play system should allow for an immediate connection and sudden situation awareness.

Vehicle-to-Infrastructure is a derivative of V2I. Vehicles communicate to the infrastructure displaying various information which is required to update the traffic network in real-time as well as the governance of safety critical data (Cai and Lin, 2008). Information includes the relaying of current position, speed etc. Infrastructure devices can include non-road bearing devices such as GPS and the forthcoming Galileo (EU GPS equivalent). Future technologies such as platooning will require new forms of infrastructure that are time-sensitive in order to deliver accurate safety critical information. Galileo for instance, which is scheduled for a 2014 activation date features 30 geographically synchronised satellites that are strategically placed around the earth's orbit with a 90% visibility ratio of 4 satellites in any location on the planet's surface. According to the European Space Agency (2010) each satellite has two atomic clocks on board capable of keeping time to within 1 billionth of a second per hour. While an analysis of this accuracy leads to the conclusion that it is still inaccurate to sustain the timing of more advanced ITS technologies such as platooning, it is a definite improvement over GPS's current accuracy performance (up to a few metres) since the accuracy of the clocks allow a triangulated position of up to 45cm. Recent breakthroughs in 2010 such as the world's first quantum clock may allow for these technologies to be implemented in the near future (Chou et al, 2010). In addition, Galileo will be fully interoperable with GPS's 24 satellites and serves to improve upon GPS's poor polar latitude service.

According to Dar et al (2010) Infrastructure based technologies are equipped with several base stations to relay communication signals over an extended range. One example of this is mobile phone networks with voice data exchange. Due to time-based requirements they have low latency at the expense of reduced reliability. Mobile networks have similar characteristics, however, the implementation is very different due to the following attributes:

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

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

Finally, driver behaviour and user acceptance while this communication mode is in operation should be monitored to be more successfully adopted (Böhm et al, 2009). Communications between the vehicle and TCC or RCC (Regional Control Centre) sends information including the current position, speed and other variables associated with the management of the traffic network. The literature argues that TCC's are acting as a distributor rather than a communication choice. Mincheva (2009) proposes that the future network will maintain a constant communication mode which is used to transmit 'global' information about the region. This form of communication is bi-direction between the vehicle and the regional control centre. The purpose of this mode is to fill in the data 'gaps' when vehicles are travelling alone in isolated conditions (such as B roads, quiet periods and country access). The type of data transmission will be long range therefore the data packets will be small compared to other communication modes. The types of data to be sent include information about the region as well as the tracking of the vehicle although certain privacy legislation may be violated unless an agreement is made. The advantages of this mode include a constant connection to the control centre regardless of where the vehicle is located as well as low levels of latency. In addition, during an event where safety is at stake the driver can contact the control centre for immediate assistance. The drawbacks to this approach include small data packets and data rate due to the distance and communication mode. Vehicle-to-X deals with the vehicle sending data to nomadic (mobile) devices which may include mobile phones, moving nodes and the provision of ICT based services in order to maintain management of the traffic network. Gil-Castineira et al (2009a; 2009b) discuss the nomadic properties of devices which would be integrated into a vehicles automotive system. They argue that consumers demand ICT services to be available at the touch of a button, therefore according to Fensels' (2007) Web

3.0 vision (the forthcoming third generation of internet based services) information is abstracted from software based around a Service Oriented Architecture (SOA). In other words, the internet from a transport network view is seen as a "*platform*" as opposed to an information repository. Devices that are not connected to an ICT system may quickly become outdated and therefore obsolete. Information related to incidents and traffic status is constantly being updated, therefore automotive systems would benefit from a constant connection to internet based services to receive safety, navigational and news updates. This communication type may also allow connection to a pedestrian mobile phone network to alert them of dangerous driving and traffic activity (David and Flach, 2010).Putting this work into the context of the thesis, a successful forecasting of ITS services required an understanding of the technical and also potential cost of the system. While some ITS services such as ISA may not require communication with the infrastructure, other more safety critical systems such as automated highway systems require constant information in order to remain active. Table 3.1 below shows the individual characteristics of a wireless connection standard compared to the applications that are on offer.

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

Table 3.1: - Communication Requirements for ITS Applications (Source: Dar et al, 2010)

The type of system architecture also has a direct impact on the level of embedded emissions and energy requirements. To estimate the sustainability of advanced services like platooning for example, the support infrastructure, the data center that resides in the traffic control centre and the vehicular network all need to be taken into account in order to give an accurate reading. Care must therefore be taken when attempting to estimate the feasibility of future ITS technologies.

3.5 Summary

This chapter has discussed the research methodology of the thesis. A performance management framework for sustainability has been introduced which aims to reduce the weaknesses associated with current ITS appraisal strategies. The methodological steps to the development of the framework were highlighted and a review of research methods performed. Methodological issues included the focus area for the framework, highlighting possible issues in terms of data collection such as the data center and scenario building for future ITS technologies. The findings from this chapter feed into the review of environmental tools that are used to conduct a sustainability assessment of ITS services in Chapter 4. This illustrates how the methods described at the beginning of this chapter were selected for the case study. Chapter 5 illustrates the development of the case study, data collection and model integration strategy from the methods that have been selected.

"ESATs are designed to assess environmental impacts of the systems studied. One of their central tasks is to evaluate environmental impacts. These take many different forms and therefore it can be difficult to comprehend and draw conclusions from a long list of environmental impact factors and their effects" (Ahlroth et al, 2011).

Chapter 4 - A Review of Sustainability Assessment Approaches for Inter-Urban Intelligent Transport

This chapter introduces the role and governance of sustainability as applied to inter-urban intelligent transport systems. It covers a range of different aspects relating to the goal of providing sustainable transport coupled with green supporting infrastructure for the governance and provision of Intelligent Transport Systems and services. An introduction to the challenges and perspectives of sustainable transport as well as current practices and the planning for a low carbon future are explored. An evaluation of the models and tools that support the decision making of ITS is illustrated and finally, a comparison of sustainability models are discussed and evaluated for the design of the EnvFUSION performance framework.

4.1 Overview of ITS Sustainability

The following sections introduce the sustainable transport field and argues why there is a need to assess the sustainability of intelligent transport in the UK and its wider effects within the European and international community. This continues the analysis from Chapter 2 of how the current problem area relates to the development of a sustainable ITS Performance Framework and Chapter 3 as part of the research methodology.

It was argued that in order to estimate performance of inter-urban ITS technologies, it was advisable to conduct a critical evaluation of contemporary environmental models, focusing on transport, the ICT field and ITS where available. The evaluation of the environmental management literature contributed to the design of the EnvFUSION framework which aims to assess the sustainability of ITS services satisfactorily for the UK's current and future baseline target emissions. From this review, the EnvFUSION framework was developed for measurement of sustainable performance in current and forthcoming technologies and services followed by a case study of one of the UK's most congested highways.

4.2 Review of Low-Carbon Models and Environmental Tools

In this section, an evaluation of models and tools for measuring environmental and socio-economic issues is carried out for the application of ITS including the most common Environmental Systems Analysis tools (ESAT[1]) which feature a combination of international standards and bear significant weight in measuring sustainable values. In addition, a description of how this relates to the successful transition to a low carbon future is discussed with an investigation of forthcoming methods and proposals in the literature. The selected models, weights and methods are evaluated depending upon their suitability for developing the EnvFUSION framework via a table listing the positive or negative contributions. Macro-economic, social and energy based models are used to explore the energy demand and carbon reduction within the transport sector. These tools are integrated into the sustainability assessment field (Bond and Morrison-Saunders, 2011). According to the literature (Odum, 1996; Dodgson et al, 2009; Finnveden et al, 2009; Higgs et al, 2010; Zhang et al, 2010) the following ESAT tools bear significant weight within the sustainable transport field and include: -

[1] This term is derived from Ahlroth (2011).

- Cost Benefit Analysis (CBA) and Cost Effectiveness Analysis (CEA)
- Multi-Criteria Analysis (MCA)
- Ecological Footprint (EF)
- Environmental Impact Assessment (EIA) and Environmental Risk Assessment (ERA)
- Standardised Environmental Management System (EMS)
- Life Cycle Assessment (LCA) and Life-cycle Cost Analysis (LCCA)
- Regional/Strategic Environmental Assessment[2] (R/SEA)

At the core of these models are weighted results which need to be presented in a coherent, accessible yet unambiguous way. According to Ahlroth et al (2011) alternatives should be easily comparable and one method of implementing this is to aggregate the results into a manageable set by using generic weighting methods. Some of these methods also share similar requirements to the weights and values, therefore improved standards and guidelines may be adopted to a large variety of ESAT models for the introduction of generic weights. Weights may be expressed in monetary terms (economic valuation) or as a basis of value and impact. In addition, consistent value methods and data sets should be developed together. In relation to ITS services for inter-urban operation, weighting methods are important in determining perceptions of how sustainable assessment should be measured and this can be achieved via identifying, classifying and selecting one or more ESAT's based upon its suitability towards a particular application. The most appropriate methods are selected resulting in the creation of the case study and data collection strategy (Chapter 5).

4.3.1 Cost Benefit Analysis and Cost Effectiveness Analysis

Once the key problems (including environmental and socio-economic) relating to transport have been identified, a variety of solutions are drawn up which are then filtered through an evaluation tool. The most common of these tools is the Cost-Benefit Analysis (CBA) where the benefits of a given project are weighed against the costs of the project known as the Cost-benefit ratio (Schade et al, 2003; Salling and Banister, 2009). CBA is based on the Kaldor–Hicks compensation principle of monetising negative externalities or ‘internalising external costs’ (Browne and Ryan, 2011).

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[2] A Strategic Environmental Assessment may encompass a variety of ESAT models as well as other strategic frameworks. See Section 4.4 for further discussion.

The origins of CBA can be traced back to 1884 when Jules Dupuit, a French engineer assessed the benefits of public sector investment projects (Dupuit, 1952). The modern CBA was developed in the 1930's in the USA where its first application was the assessment of water resource projects. Therefore, a significant body of early work is based upon water and river resource development (Simpson and Walker, 1987). Within the UK, this process begun in 1967 as CBA became a formal method approved and practiced by the government (Kula and Evans, 2011). During this period, the principles of CBA applied to transport projects were given practical detailed effect through programmes of theoretical and empirical work on, for example, the relevant monetary values for time and safety benefits (Grant-Muller et al, 2001).

CBA has now been initiated globally becoming a key method in many road network operators and appraisal frameworks. Stevens (2004) highlights that CBA is a society wide application of investment appraisal that is used by private companies and it can be applied to a variety of different projects including large and medium sized road infrastructure. According to Thomopoulos et al (2009) the driving principle of CBA compared to other appraisal methods is that it allows decision makers to compare various alternative options based on a single value: the Benefit-cost ratio (BCR). The core benefit is that all impacts are quantified and expressed in monetary terms, which might also be more comprehensively reported by decision and policy makers, and it offers the opportunity for easier comparisons among diverse alternative options.

CBA and its discounting method has a critical impact upon determining the feasibility of current and future road transport projects. When it comes to significant indirect effects in the economic, social, and environmental systems connected with the transport system, alternative approaches to the microeconomic approach become inevitable. Sentence (2009) argues that in order to create and maintain a low carbon policy it is necessary to implement emissions trading (ETS) and taxation where both mechanisms have individual benefits, however, not all parties may perceive the mechanisms as a positive measure. It is also recommended that they be suited to a particular region or sector, therefore the literature recommends a sectoral approach (Fujiwara, 2010; Millard-Ball, 2010).

ETS is already in operation within the EU as it an implementation mechanism of the Kyoto Protocol (a powerful legally binding contract) and is the largest implementation of a cap-and-trade scheme worldwide (Kettner et al, 2010;

Millard-Ball, 2010; QA Ltd, 2010). For all annex-1[3] countries this is an optional method of meeting the emissions targets stated in the Kyoto contract (Figure 4.1). Since the protocol expires in 2012, there is concern that the targets and baselines are not stringent enough to mitigate climate change (Click Green Website, 2010). According to Iwata and Okada (2010), the Kyoto protocol delivers a negative response with regard to commitments to CO_2 and CH_4 emissions, are not significant for the case of N_2O emissions and significantly positive for the case of other greenhouse gas emissions. The results have serious policy implications for global warming issues.

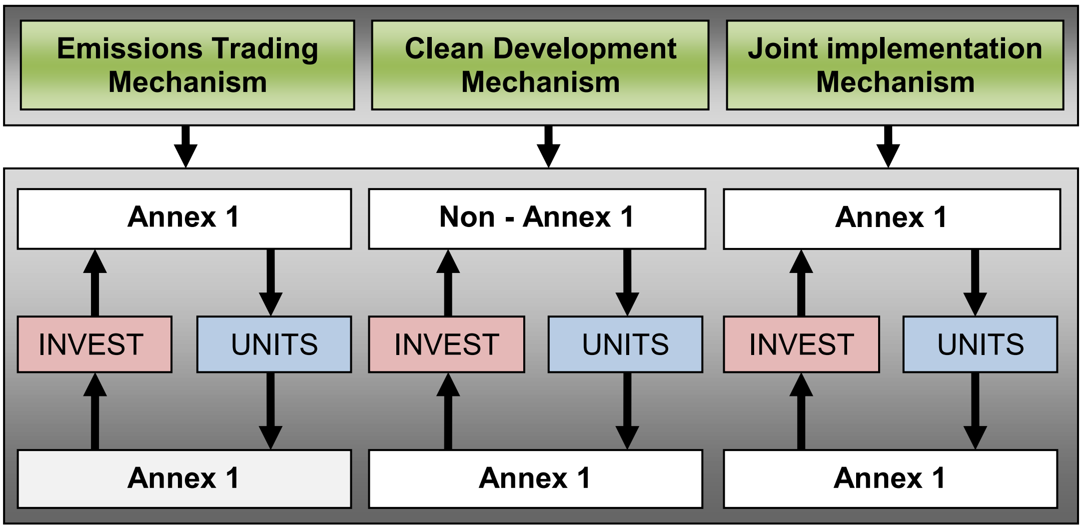

Figure 4.1: - Kyoto Mechanisms (Source: QA Ltd, 2010)

Traditionally, CBA's use fixed or linear data sets with at least one year's historical data for calibration and one year in the future for forecasting and impact analysis. While this may be acceptable for small or localised projects, larger projects may pose wider ranging impacts, making the traditional CBA approach impractical. In order to counter this deficiency, Schade et al (2003) developed a system dynamics platform in order to assess the marginal cost and benefit over a longer period via altering the welfare impacts via the change in variables. This was developed via a European research project known as the Assessment of Transport Strategies (ASTRA).

According to Almansa and Martínez-Paz (2011), CBA is currently being modified via two different perspectives. Firstly, the development of a new toolset

[3] Annex 1 countries represent the countries that have signed and ratified the Kyoto Protocol. By this period (2011) 191 states or regions have signed and ratified the protocol.

which aims to measure the valuation of environmental aspects which were orginally rejected from the analysis due to an incompatability with the CBA specification (aspects are rejected if they do not interface with the economic valuation). In high environmental projects with a long term effect on future generations, assigning the discount rate to the time horizon (where emissions can span centuries) is of high importance due to the potential variance in profitability assessment. Probabilistic criteria as opposed to exact values is desired due to the ability to integrate uncertainty assessments such as Monte Carlo analysis. The second approach is a longer process which deals with the constant revision of the underlying theory of the traditional approaches of discounting. Because climate change features repurcussions over a long period of time, current discounting models only deal with assessment over a couple of decades. Kula and Evans (2011) conducted a case study for treating environmental benefits separately within the framework of the sustainable development field and applied dual discounting to an afforestation project within the UK. The results gave environmental benefits such as carbon offsetting as well as conventional benefits and would therefore enhance the economic viability of investment projects. As with discounting, the focus is on the present and short-term estimate. Therefore dual discounting should be applied and sustainability should be addressed independently from economic appraisal, although recent efforts have been taken to project discounting into the future (Almansa and Martínez-Paz, 2011; Lai et al, 2012).

CBA is widely dismissed due to its one-dimensional monetary valuation judgments, a lot of criticism has been aimed at CBA which focuses on the discount rate or the appraisal period to be used:

> *"CBA attempts to attach monetary values to all these costs and benefits even though externalities (such as casualty or pollution reductions) are notoriously difficult to quantify...Since users are not asked to pay directly for the benefits, they have to be estimated on the 'willingness to pay' principle." (Stevens, 2004)*

Those issues have long been discussed by scholars and there are advocates and critics on either side. Simpson and Walker (1987) illustrated three major drawbacks of CBA. The authors condemned its one dimensional approach which monetizes all benefits regardless of stakeholder perceptions. They also denounced its ability to handle uncertainty and risk in which only a few variables are relative to the outcome of the analysis as well as the extent and nature of the uncertainty surrounding each of the critical variables, which tend to differ. The last issue identified was intergenerational bias where assessing the discount rate over a period of more than 20 years leads to wildly conflicting and inaccurate results. For example, there are proponents of high discount rates, low discount rates or even no discount rate. The literature identifies a number of CBA studies applied to current and anticipated ITS systems which is shown in Table 4.1.

Review of CBA/CEA Applied to Intelligent Transport Systems

ITS Technology	Country/Region of Study	Literature	Total Number
Active Traffic Management *incl. Variable Message Signs*	France	(Motyka and James, 1994)	4
	USA	(Sisiopiku et al, 2009)	
	Canada	(Schnarr and Kitaska, 1996)	
	Finland	(Nokkala, 2004)	
Automated Highway System	Generalised	(Ran et al, 1997)	3
	Germany/Japan	(Baum et al, 1999; Baum and Geissler, 2000)	
Advanced Driver Assisted Systems	Norway	(Shibata, 1992)	5
	UK/USA	(Jeffery, 1981; Harvey, 1994)	
	UK	(Carsten and Tate, 2005; Lai and Carsten, 2012)	
Travel Information System	USA	(Lee Jr, 2000)	1
Combined/Strategic Analysis and Frameworks	UK	(Perrett et al, 1996)	5
	EU	(James, 1999; Psaraki et al, 2012)	
	USA	(Yun and Park, 2004)	
	N/A	(Stevens, 2004)	

Table 4.1: - Studies of CBA applied to Intelligent Transport Systems

According to Stevens (2004), CBA offers various advantages in measuring sustainable ITS performance. It uses established economic principles in order to assign values and therefore is able to decide if the investment is worthwhile to society from a holistic perspective. It may also be required in order to secure public or private sector funding which judging by the current political climate should help encourage environmental stability within ITS. From an environmental standpoint, modifications to the CBA methodology may allow the measurement of environmental ITS performance to become a reality.

> *"In its application to ecosystem services, cost-benefit analysis is informed by the ecosystem services framework, a metaphor of nature that conceives of the environment as natural capital, and of natural processes as leading to a stream of ecosystem services that flow like 'interest' from the natural capital to society" (Wegner and Pascual, 2011).*

Stevens (2004) explores the typical methodology for ITS project investment and is illustrated in Figure 4.2 below.

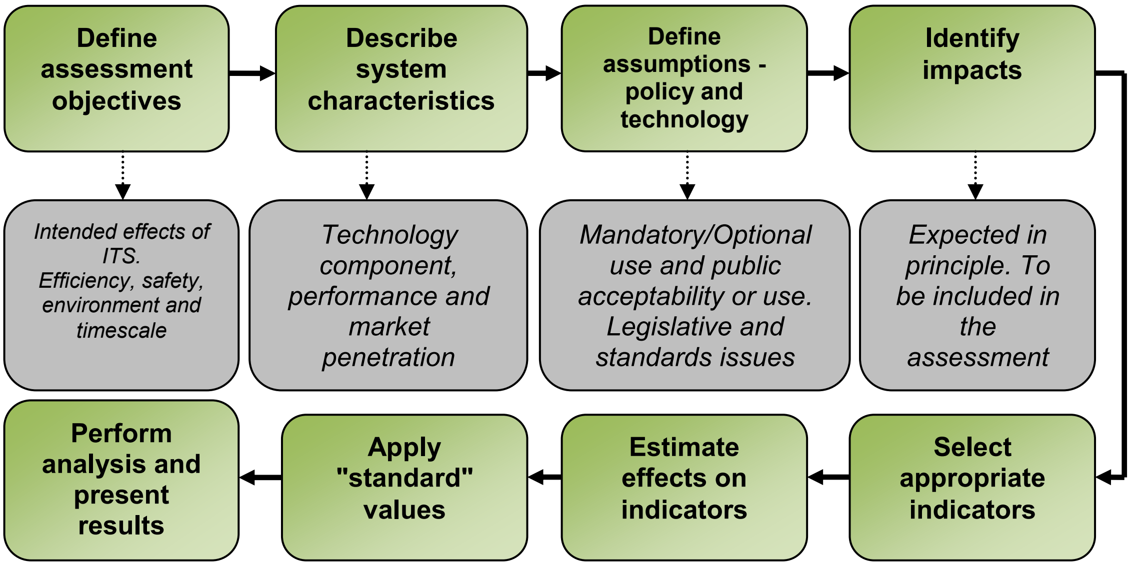

Figure 4.2: - Typical ITS Cost Benefit Methodology (Source: Stevens, 2004)

The Department for Transport (DfT) carried out a study which attempted to assess the cost and benefits of ITS within the UK (Perrett et al, 1996). This study developed various implementation scenarios for each application of ITS. The results forecasted strong social benefits towards inter-urban road transport. Distinctive benefits were related to automated speed control and speed enforcement as well as notable social benefits including vehicle automation such as AHS. Current inter-urban applications would typically include Ramp control, Incident control, Area control, Speed control, Lane control, Electronic tolling and Demand management. However, road user charging did not give any monetary benefits. Other notable studies in the 1990's included an analysis of ITS performance via the European project CITY PIONEERS which assisted in project guidance for local regions and areas for implementing ITS applications. The introduction of simplistic ITS performance indicators were also the subject of another European project, MAESTRO (James, 1999). The Maestro guidelines were the culmination of a 21 month project backed by the European Commission which focused upon assessing the applicability of new technologies and services from theory to implementation. Lai et al (2012) conducted a CBA on the reduction of accident occurrence and fuel consumption for Intelligent Speed Adaptation (ISA) using two independent market penetration scenarios: market driven, where the popularity of the technology determines the share at a particular year and authority driven, where speed reduction becomes mandatory. Overall, the cost benefit ratio for the market scenario up to 2070 was 3.4 while the authority scenario was 7.4. Stevens argues that for any measures of performance, validity, reliability and sensitivity all play a key role for the measurement of successful applications and services.

CBA, as a sole ESAT tool, possesses distinct disadvantages that hinders the approach taken for ITS service appraisal and draws parallels with issues already discussed within the literature. Firstly, a lack of experience and validity means there is no reference point to base the initial appraisal. Traditionally, CBA is calibrated based upon past projects and due to the lack of historical data, the accuracy of the cost benefit assessment may suffer and an estimation of expert judgment is given instead. In addition, the appraisal due to time, scope and budget constraints may not be performed successfully, jeopardising the accuracy of historical data for use in future projects. Dis-benefits such as issues of climate change for example do not get reported satisfactorily although Stevens (2004) argues that publicising project side effects such as pollution exponential may compromise the readiness and support of future transport projects. The counter-argument is that environmental transparency is considered very high on the political agenda, therefore the impact on the environment must be documented thoroughly. The valuation outcomes such as willingness to pay or accept are aggregated figures and are based upon values such as income. The methods used to value the impacts (stated preference and hedonic pricing etc) may not be completely adequate to value effects and the knowledge base to estimate long-term impacts may be missing. Policy judgements are therefore required and may usher expert opinion. The valuation of environmental impacts over a long-term period may not be feasible using a sole CBA method as qualitative values such as social, safety and welfare cannot be processed through this methodology without modification in the discounting method, although recent research suggests approaches such as dual and declining discounting may allow such issues to be tackled in the future.

With regard to the proposed EnvFUSION model, it is apparent that CBA cannot exist as a sole entity capable of assessing the operational status of an environmental assessment within ITS. However, in tandem with another tool it may become a powerful appraisal 'option'. It may be used to estimate the cost implications of harnessing environmental efficiency or (even inefficiency) within the current scenario. Serious problems arise however when attempting to estimate appraisal at the medium (20 years) or long-term (30+ years) due to large uncertainties in economic forecasting without modification, although recent innovations in the discounting method allow for a more accurate long-term forecast.

Table 4.2 gives a summary of the critical evaluation of CBA, featuring the advantages and disadvantages along with a grading of the positive and negative impacts each aspect of the method has that would contribute to the proposed EnvFUSION framework.

Evaluation of CBA/CEA's expected contribution to EnvFUSION

Advantages	Positive Indicator	Disadvantages	Negative Indicator
Can be applied to a wide variety of projects.	Seldom	Relies heavily on historical data.	Very High
Useful for assessing the value of monetary gain.	High	Requires resources which take time to integrate therefore affecting budget.	High
When working in tandem with other environmental tools (MCA, Impact assessment etc), CBA becomes a powerful appraisal method within a larger framework.	Very High	Lack of reporting on dis-benefits (i.e. weaknesses of approach adopted after decision is made.	Seldom
Modifications to existing methodology may allow a recalibration of the tool to sustainable assessment (i.e. dual discounting etc.)	High	Over-reliance on valuation and monetary methods.	High
		Methods used to value impact are not adequate to value effects.	High
		Knowledge base to estimate long-term impacts may be missing. Expert opinion required.	Very High

Table 4.2: - Evaluation of Cost-Benefit Analysis

4.3.2 Multi-Criteria Analysis

Other tools that can be aligned to sustainability include Multi-Criteria Analysis (MCA) which forms a large part of the Multi-Criteria Decision Making (MCDM) approaches. Dodgson et al (2009) refers to MCA as a set of pre-defined approaches[4] that offer a variety of solutions compared to CBA, which can be referred to as a unified set of techniques. Key differences include CBA being based

4 Note that CBA and MCA have been combined in some sectoral and strategic frameworks.

on economic efficiency criteria such as the Net Present Value while MCA incorporates other types of criteria such as distributional, equity, ecological and so on. Alternatives in CBA are evaluated by performance criteria that are measured in monetary terms as opposed to not being based exclusively on monetary valuations and finally a CBA only supports quantitative data while MCA may use both.

In some cases, MCA is also combined with CBA. Because CBA is used alongside other forms of assessment, a more inclusive approach is required in order to conduct transport appraisal across not only current transport projects but also future road transport proposals (Ahlroth et al, 2011; Barfod et al, 2011; Gühnemann et al, 2012). MCA techniques can be combined with CBA in the form of a decision support system and this is partly the case with some national appraisal frameworks. There are cases when no satisfactory values exist for some elements/effects which nonetheless are considered significant to be included in the appraisal. This is where MCDM techniques may assist.

Early research in applying decision support to transport planning consisted of developing a multi-criteria cost benefit analysis. The European Commission's fourth framework project - EUNET (European Commission, 2001) applied scores to the investment criteria such as the benefit cost rates, treating the rates just like any other criterion. Sayers et al (2003) offered a similar approach and concluded that widespread use of the method could lead to a far greater degree of accountability and transparency in the process of transport investment appraisal (DfT, 2011) without sacrificing decision-takers' ability to exercise some discretion in the process. Barfod (2011) developed a decision support tool known as a composite model of assessment (COSIMA) consisting of the sum of benefits in CBA and the pair-wise comparison of the analytical hierarchy process (AHP), an MCA method. Finally Gühnemann et al (2012) incorporated CBA results into an MCA framework in order to prioritise a national road infrastructure programme. The approach retains the strengths of each appraisal method and provides a procedure for decision makers to create an initial ranking of projects which is consistent between all candidate investments and has a clear link to policy goals.

The advantages of MCA according to measuring sustainable ITS performance is its ability to manage complex sets of information which would burden the typical transport planner. For example, a number of emissions and energy analysis scenarios proposed by Hickman et al (2012) demonstrated using a hybrid methodology that combines scenario testing, MCA, multi-actor participation and visualisation/simulation techniques, so that comparison of multiple sustainable transport scenarios against MCA impacts could take place. Objective setting and assignment of weights to particular criteria is also a core feature of most MCA methods compared to a identified lack of weight assignment in CBA (Pearce et al, 2006). When a high level of detail is deemed essential for the objectives and criteria used, MCA techniques offer various ways of aggregating the data on individual criteria to provide indicators of the overall performance of options. One key feature of MCA techniques is the emphasis posed on the judgment of the decision making team or an individual, establishing objectives and criteria as well as estimating relative importance of weights and within a certain extent in judging the contribution of each option to each performance criterion. MCA also has the potential to bring a degree of structure, analysis and openness to classes of decision that overcome the practical reach of CBA.

As described above, one MCA method is AHP, a technique pioneered by Thomas Saaty (1980) in order to organise and analyse complex decisions. According to Brucker et al (2004) it 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: construction of a hierarchy, priority setting and logical consistency (Saaty, 1990; Hermann et al, 2007; Sambasivan and Fei, 2008). The hierarchy of AHP is a highly complex system which is derived from a single element at its plateau consisting of the main objective or focal area. Intermediate levels represent sub-objectives and constituent parts, ideally being assessed by operational criteria. The bottom or foundation levels represent the final actions or decisions to be implemented. Arrows describe causual relationships within the hierarchy. Saaty (1990) maintains that a sufficient level of detail should be included in order to represent the problem as thoroughly as possible but not so thoroughly as to lose sensitivity to change in the elements, to consider the environment surrounding the problem and to identify the issues or attributes that contribute to the solution and finally, identification of the participants surrounding the solution.

There are some drawbacks to using the MCA approach. The degree of subjectivity that exists in this process (assignment of weights in MCA) has provided concerns regarding such techniques. In France, this resulted in the eventual rejection of MCA (Quinet, 2000). Also, the criteria to be used may be subjective, but this scenario may be encountered in CBA too. It has been noted by Thomopoulos et al (2009) that too often decision makers do not explicitly select one ethical perspective over another, resulting in questionable appraisal outcomes. A significant flaw with MCA is its lack of support for measuring social aspects of sustainable transport such as welfare based upon the benefits that have been chosen. It cannot show how the benefit adds more than it inhibits which may be a critical feature of preserving environmental change (Dodgson et al, 2009).

A limited number of studies have been conducted on ITS using the multi-criteria decision methods and have mostly focused around a combined strategic analysis in supplier choice, technology selection and planning (Brucker et al, 2004; Jung et al, 2007; Khademi et al, 2010). Ghaeli et al (2003) proposed an integrated project portfolio selection model using AHP and proven concepts used for portfolio selection in the finance discipline. The new methodology facilitates decision making by integrating both the risk and the value of projects. Agusdinata et al (2009) presented an innovative MCA approach based on exploratory modelling to handle uncertainties surrounding ISA policymaking. This approach uses computational experiments to explore the multiple outcomes of ISA policies (safety, emissions, throughput, and cost) across a range of future demand scenarios, functional relationships for performance criteria, and user responses to ISA.

Methods such as the AHP and Analytical Network Process (ANP) can assist in prioritising ITS services against alternatives. Jung et al prioritized six ITS services using ANP, which considers mutual dependence between the evaluation items and alternatives. AHP is a one-way process that does not consider the independence of feedback from the services. According to the results of their super decisions ratings, the Regional Traffic Information Center System was chosen to be the top priority project followed by the Urban Arterial Incident Management System and the Bus Information System.

Khademi et al (2010) illustrated 33 ITS user services through a hybrid model of the disjunctive satisfying method (DSM) and ANP. The DSM reduces the problem size by excluding inappropriate user services while the ANP establishes overall relative preferences for selected user services by considering various inner dependencies, interdependencies, and mutual effects among the elements. The electronic payment, travel demand management, and traffic control user services were proposed as the best alternatives for the problem in a developing country.

Lasdon and Machemehl (2005) used the Elimination and Choice Expressing Reality (ELECTRE) method to address problems resulting from comparing various ITS deployments. A modified ELECTRE-I method was developed to compare a number of ITS alternatives with respect to multiple objectives. By varying the weighting scheme to favour different criteria and performing a sensitivity analysis, the nominated alternative was identified.

For this research, Active Traffic Management, comprising its road-side infrastructure and ICT data center could be categorised into an ITS sustainability index which could be normalised using the Analytical Hierarchy Process (AHP). According to Brucker et al (2004) and Saaty (1990) criteria within MCA can be generated spontaneously. In a bottom-up perspective, the criteria are developed based upon the cause and effect relationship of a specific action or choice. This approach seems very applicable for EnvFUSION due to spontaneous criteria generation and its transitivity properties (Awasthi and Chauhan, 2011). It is possible in this research to enhance methodological development for the EnvFUSION framework using the MCA approach, which is considered more appropriate as it fulfils many of the deficiencies of CBA (or Distributional CBA). However, to take into account the numerous stakeholders involved within ITS and to manage the social, economic and environmental perspectives, this method would have to be developed using a two-tiered priority system which could weigh the criteria based upon a performance ranking system where experts would rate the criteria as well as provide anticipated targets. Weighted priorities could be given for each pillar of sustainability as well as the individual criteria. Utility values could determine if emissions are improving or declining by experts and whether targets have been achieved based upon if they are exceeding or falling short. However, another method may have to be proposed in order to handle the identification and ranking of such targets. Table 4.3 provides a summary of the evaluation of MCA.

Evaluation of MCA's expected contribution to EnvFUSION			
Advantages	**Positive Indicator**	**Disadvantages**	**Negative Indicator**
Manages complex sets of information.	High	Subjectivity exists which makes quantifying some attributes and indicators difficult. Criteria used may be subjective.	High
MCA techniques such as AHP can aggregate data on individual criteria to provide indicators.	Very High	Lack of guidance on ethical perspectives.	Low
Matches effectiveness of each option to performance criterion.	High	Some MCA approaches do not provide detailed decision making rules or influence the decision at all.	Seldom
Establishes a degree of structure, analysis and openness to classes of decision. Other tools may be incorporated into the analysis (CBA etc) to become more powerful.	Very High	Lack of support for Social aspects (i.e. welfare etc). It cannot show how the benefit adds more than it inhibits which is a critical feature for preserving environmental change.	High

Table 4.3: - Evaluation of Multi-Criteria Analysis

4.3.3 Ecological Footprint - Appropriated Carrying Capacity

An Ecological Footprint (EF) in its simplest form represents the rate that humans deplete the earth's natural resources compared to the ecosystems rate of recovery (Wackernagel et al, 1994; Global Footprint Network, 2009). Originally developed by William Rees and initially termed 'Appropriate Carrying Capacity', the first academic publication concerning EF was issued in 1992 (Rees, 2005). The concept was developed further by Wackernagel in the form of a PhD thesis supervised by Rees. Wackernagel's academic defence "shows that the EF/ACC concept can link global, social and ecological concerns to individual and institutional decision-making" (Wackernagel et al, 1994). The assessment area is based upon the amount of natural land and marine resources required to sustain human life and services and the waste that is produced as a by-product of sustaining modern lifestyles (Kitzes et al, 2009).

> *"Since living renewable resources regenerate using solar energy, a population Ecological Footprint can be said to represent the area continuously required to generate a quantity of photosynthetic biomass energy and material equivalent to the amount used and dissipated by the population's consumption" (Kitzes et al, 2009).*

According to Siche (2010) the ecological footprint represents one of the most important assessment tools in evaluating the biophysical limits of the ecosystem as well as appraisal of environmental performance of human based systems. Footprint data values at the end of a sustainability analysis are categorised for Carbon, Housing, Food, Goods and services and can also in a similar way to a lifecycle analysis be related to the manufacturing of a product. By utilising other tools in combination for verification after the calculation of the ecological footprint such as the Emergy[5] Net primary production, the results give an improved reflection on the ability of the ecosystem to support human dominated systems. Improvements to the Ecological Footprint in the past 16 years since its conception has since seen the creation of the Global Footprint Network which have recently produced a set of standards which may optimise the ecological footprint analysis (Global Footprint

[5] Emergy is the available energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service (Odum, 1996). Emergy accounts for, and in effect, measures quality differences between forms of energy. Emergy is an expression of all the energy used in the work processes that generate a product or service in units of one type of energy. The unit of emergy is the emjoule, a unit referring to the available energy of one kind consumed in transformations.

Network, 2009). The standards, created in 2006 were produced under guidance by a committee and validated in two public review periods. Standards that cater for the modern organisation are currently under discussion.

EF analysis in the context of road transport can be calculated according to Rendeiro Martín-Cejas and Pablo Ramírez Sánchez (2010) using road network data such as volumes of traffic, types of vehicles, vehicle fuel efficiencies and the physical dimensions of the road network. In their paper, they attempted to discover the ecological footprint of road transport related to the tourism industry upon Lanzarote island. The transport road network may also be represented numerically using a matrix. Typically, the columns and rows of a matrix represent the origin and destination while the numerical value within a matrix cell displays traffic flow between an origin and destination within the road network.

EF does possess some disadvantages. Firstly, EF does not cover the untouched area of the environment nor does it extend its analysis beyond CO_2 to other GHG emissions which is a major concern as some emissions carry greater burden than CO_2 as discussed by the IPCC (2001). In addition, based upon the results of a recent Emergy analysis, the indicators may underestimate the level of human carrying support. Wackernagel reinforces this argument through stating:

> *"Are the Ecological Footprint results correct? Certainly, one thing we can be sure about when looking at the results is that they can never be wholly accurate. And that goes for any model — the results of a model are always an approximation. The operative question is rather: Are the model's results accurate enough to be useful?" (Wackernagel, 2009)*

Utilising an EF within the case study may illustrate how an ITS service is environmentally stable enough to coexist with the global resources. However, it does not seem to possess enough focus as a singular form of low carbon assessment. Table 4.4 illustrates the evaluation of ecological footprint.

Evaluation of EF's expected contribution to EnvFUSION			
Advantages	**Positive Indicator**	**Disadvantages**	**Negative Indicator**
Uses a simple mathematical formula to consider the effect of the consumption of society (Footprint) in its natural environmental (Bio capacity).	Low	Does not consider the work of untouched nature in productivity and ecosystems services.	Low
incorporates a vast amount of information in a simple quantitative measure to express its results (land area in global hectares).	High	Area of analysis is for CO_2 emissions only and is based upon forests ability to absorb CO_2 gas.	High
		Considers each area only once, although the same area may be supplying two or more ecological services.	N/A
		Use of energy is accounted for as fossil fuel by means of carbon dioxide emissions, not possible to evaluate EF from the use of the required land area (bio fuel etc).	High

Table 4.4: - Evaluation of Ecological Footprint

4.3.4 Environmental Impact Assessment and Environmental Risk Assessment

The Environmental Impact Assessment (EIA) was initially introduced in order to overcome the limitations of the classical CBA and involves subjectivity, conflict and uncertainty (Colorni et al, 1999). These limitations are particularly evident in the case of transport infrastructure. While both social cost and generalized travel cost must be considered, these may include intangibles such as social damage from air pollution or risk to life that can be difficult to express in monetary terms and a monetary criterion is not always acceptable from a social viewpoint (Colorni et al, 1999). According to Pölönen et al (2011) EIA can be described as a preventive environmental policy and management tool. It has been adopted worldwide to assess the environmental effects of projects, plans and programmes in a systematic and comprehensive manner.

A related procedure is the Strategic Environmental Assessment (SEA), which has as a goal to include environmental impacts into strategic decision making by administrative bodies (see Section 4.3.7). More specifically, it applies to strategic decisions in governmental policies, plans and programmes (Koornneef et al, 2008). Public decisions regarding transport infrastructures which produce major environmental, social, and territorial impact can be facilitated by this method. One if its key functions is to provide a forum for public participation (O'Faircheallaigh, 2010).

The essence of EIA is its ability to broaden the information base for decision making in order to produce planning, policy and development choices. Therefore it is not a single technique but a decision procedure that may exploit a number of different techniques such as CBA, Lifecycle Assessment and risk analysis. According to Zhang et al (2010) EIA although similar to Environmental Risk Assessment it is not an alternative due to its inability to evaluate and manage the hazards to life and the environment such as contaminants and leakages of hazardous substances. EIA is required for projects that carry a greater environmental burden while ERA is often voluntarily carried out via agencies to assist in their decision making. EIA attempts to reinforce compliance with regulation requirements while risk assessment can be used in the following manner:

> *"(1) to determine whether the risk posed by agents meet the regulation requirements; (2) given the predefined risk (usually the regulation requirements) to determine the thresholds of disturbances on ecosystem or set the remediation target." (Zhang et al, 2010)*

The latter is used to determine the remediation criteria for pollutants in contaminated sites due to a lack of regulation requirements. EIA is criticized due to its lack of rigid quantitative methods to predict the probability of the potential effect on the environment. In risk assessment, measurement frameworks for risks posed by substances exist such as human health risk assessment, ecological risk assessment, and comparative risk assessment as well as more detailed models that feature contaminant transport and transformation models. They can all be used to identify the criteria to be used in ranking contaminated sites and when more information becomes available, environmental indicators can be used to prioritize them.

Uncertainty must be correctly represented and transparently incorporated within the risk assessment. The uncertainty analysis must be incorporated into each step and the cumulative influences on final risk evaluation have to report to the risk managers. Compared with EIA, uncertainty representation and propagation are not discussed transparently. It is correct to say that EIR and risk assessment can cooperate together in order to produce better guidelines and decision making, as the methodology used in ERA known as stress response analysis can be used to evaluate the potential environmental impacts caused by the projects (for example the construction of a dam on a river). Therefore ERA can be considered as a complement to EIA. According to the literature a number of EIA's have been carried out on transport appraisal. Colorni (1999) developed a decision support system known as SILVIA (an Italian acronym meaning Interactive Software for EIA). SILVIA can be used both as a coordinating tool to deal with qualitative and quantitative estimates from different disciplines and as a means of communication and participation.

To the best of the authors knowledge, no studies on EIA/ERA have been conducted on ITS due to the majority of current schemes not requiring significant change in land use and to a greater extent this is the benefit of ICT utilisation. A typical EIA may struggle to estimate the performance of systems that are ubiquitous in nature due to its focus on a localised area while ERA is focused upon damage assessment and mitigation. Therefore these methods were considered out of scope for the research. Damage assessment for ITS is presumed to be marginal as opposed to the widening of a stretch of road. Active Traffic Management for example requires little or no additional land-use as its goal is to utilise existing infrastructure and any form of manufacturing is carried out off-site with the changes in vehicle emissions a marginal by-product. The data center is also off-site with its own separate performance specification. Undertaking a traditional EIA/ERA would therefore be unfeasible as all of the stakeholders must be involved at a detailed level in order for it to be useful. As it is only carried out in the planning and post-implementation phase of transport appraisal it cannot solely be used to assess the operational performance of an ITS scheme or project into the future. What the potential long-term change in terms of environmental and socio-economic performance will be based upon is technology improvement, although scenario analysis has been considered as an extension to the approach (Duinker and Greig, 2007). As the basis of this research was focused on assessing the internal sub-systems that contribute towards the optimisation of ITS schemes, ERA was out of scope for the study while EIA as procedure was not required due to other methods being more readily available. Table 4.5 shows the evaluation of EIA/ERA's to the proposed study.

Evaluation of EIA/ERA's expected contribution to EnvFUSION			
Advantages	**Positive Indicator**	**Disadvantages**	**Negative Indicator**
Can assess the potential risks and benefits of an ITS project in the planning phase.	High	It can be a resource intensive method due to the number of potential methods in use.	Seldom
By making the information on the likely significant effects available, EIA can help allay fears created by a lack of information.	High	Any lack of knowledge in the impacts or external surroundings may result in a poor assessment.	High
		The normalization of the decision process requires both strong technical interdisciplinary and active participation of the social groups involved.	High
		This leads to a high degree of conflict due to the contribution and opinions of multiple stakeholders.	High

Table 4.5: - Evaluation of Environmental Impact/Risk Assessment

4.3.5 Standardised Environmental Management System

Industry and the production process has largely accounted for the rise in global pollution, therefore to counteract this change and restore equilibrium to the environment organisations must adopt new standards and protocols. It is important to note that an organisations' main goal is profit, but increased social awareness has lead to the integration of environmental, social and economic issues within its culture.

> *"Modifications in processes that can cause environmental impacts are being introduced in industries little by little, especially in emerging countries, and they are even applied in product development." (de Oliveira et al, 2010)*

The standardised EMS is a procedural tool for an organisational management system which offers structured and effective management of environmental issues in organisations. It includes relational dependencies such as organisational structure, sharing of responsibilities and planning of practices, procedures and resources required to determine and achieve policy objectives. The EMS is mainly designed in accordance with the Plan, Do, Check and Act cycle or PDCA (Langley et al, 2009) and includes environmental review, formulation of policy, setting of environmental objectives, improvement work, auditing, corrective actions and management review. For example, the planning stage includes environmental policies, environmental impacts and environmental goals. 'Do' relates to environmental activities and environmental documentation. 'Check' refers to the verification of environmental audits and assessment of environmental performance. Finally 'Act' is based upon the training and communication to increase the awareness of sustainability issues for the staff.

EMS's are conceived and developed for a variety of different roles. According to de Oliveira (2010) an EMS can be defined as a methodology in which organisations should operate within a structured manner in order to ensure environmental issues are accounted for. The tethering of environmental protection to an EMS can produce the refinement of products and processes or can result in the introduction of radically new green technologies.

> *"...improvement(s) affect different dimensions, such as material intensity (efficient use of materials), energy intensity (efficient use of energy), transport intensity (efficient logistics), surface intensity (efficient use of space) or risk intensity (related to factory floor plan, substances and products)." (de Oliveira et al, 2010)*

Various standards exist which act as guidance to ensure the EMS is meeting stringent quality checks. These standards are necessary to ensure the EMS can harness the planning objectives, activities and the introduction of suitable metrics. One standard in particular is ISO 14001 which aims to provide an internationally recognised framework for the assistance and maintenance of sustainability issues within an organisation. This includes the introduction of measurement, evaluation and auditing guidelines. What is important to note is that 14001 does not introduce performance indicators but provides a tool which helps to manage and control the environmental status of the organisation. In addition, the standard may include the following categories for improvement:

- Environmental Auditing
- Environmental Labelling and declarations
- Performance Evaluation
- Environmental Management
- Lifecycle Assessment

Gavronski et al (2008) highlights various advantages that the ISO 14001 standard and its supporting standard ISO 14004 produces both from internal and external perceptions. Internal improvements relate to increased financial performance and service productivity while external benefits lead to enhanced social acceptance from society, stakeholders and a competitive market environment. However, further analysis is needed to determine the disadvantages, consequences and repercussions of gaining certification and what it means for the organisation.

A significant advantage of EMS over other ESAT methods is its ability to monitor the whole lifecycle while other models tend to only measure one part of the process. Every stage of the production process can benefit from the integration of green engineering and its benefits (Oliveira and Serra Pinheiro, 2009). Therefore, an organisation is pushed to create green standards for their services. One example, includes the adoption of guidelines for green IT as part of a company's continual service improvement programme (Crooks et al, 2009; Ruth, 2009). Other benefits include access to new markets, increase in market share, management in compliance with legislation, regulatory incentives, reduction in risks, better access to insurance and more capital. In addition, improvement in the production process, environmental process, general management of the company, employee relations, public image, competitive advantage in significant segments. Finally, meeting client demands, improved quality of life, clean (green) operations, improved product and service competitiveness and public awareness (Gavronski et al, 2008; de Oliveira et al, 2010; Ahlroth et al, 2011).

Several weaknesses exist within EMS. Firstly, there are no recognised weights within the method which leads to a degree of ambiguity when determining how to assess sustainability. Although it can be argued that this increased personalisation to a specific organisation provides a benefit nevertheless, it increases responsibility to develop weighting methods to interpret the environmental status of the company which in turn requires a deeper knowledge of how the organisation operates. Also, some aspects are quantifiable and some are not. For example, social acceptance, level of effort concerning green uptake and public image resulting from the promotion of environmental maturity are very difficult to quantify. According to a study by Ahlroth (2011) almost half of the companies under scrutiny used non-related technical and monetary data in their analysis of environmental performance.

> *"Most organisations are forced to deal with a mix of aspects that are not quantified, quantified but with no clear link to environmental impact, and quantified according to the type of environmental impact that arises." (Ahlroth et al, 2011)*

Due to the ambiguity in the EMS framework, importing monetary and metrics unrelated to sustainability, key environmental factors may become under-prioritised if they are too expensive to correct or infeasible due to a technical complication.

EMS may be utilised due to its ability to monitor the whole lifecycle and as every stage may benefit from green engineering, the EnvFUSION framework may benefit from the holistic contribution that EMS may bring by switching the perspective of performance assessment to the organisation and the identification of emissions at multiple sites. Although this may require a more detailed analysis of the road network operators facilities, EMS as a standalone method may be too ambiguous due to the lack of developed weighting methods of the road network operator and the scope of the research would have to be widened in order to take into account the organisations assets which would be impractical. Table 4.6 illustrates the evaluation of EMS to the proposed framework.

Evaluation of EMS's expected contribution to EnvFUSION			
Advantages	**Positive Indicator**	**Disadvantages**	**Negative Indicator**
Ability to monitor the whole ITS lifecycle due to an embedded lifecycle analysis within its methodology.	High	No recognised Weights leads to ambiguity in determining how to assess sustainability.	High
Every stage can benefit from green engineering therefore encouraging production of green standards.	Low	Sporadic data sets when cross referencing different EMS evaluation due to organisations using own metrics/weights.	High
Improvement in the production process, environmental process, general management of the road network operator.	Seldom	Some aspects not quantifiable (e.g social acceptance, level of effort and public image).	High
		Importing monetary and non-monetary metrics unrelated to sustainability may under-prioritise key environmental factors.	Very High

Table 4.6: - Critical Evaluation of EMS

4.3.6 Life Cycle Assessment and Life Cycle Cost Analysis

The life cycle assessment (LCA) 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. Currently, it has been vastly improved including recalibration and harmonisation within the methodology which consequently leads to clearer results.

LCA techniques have 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 improved 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 approaches, although two are dominant i.e. 'attributional' and 'consequential' (Rebitzer et al, 2004; Finnveden et al, 2009; Mathiesen et al, 2009). The attributional approach is essentially a point estimate in time and is calculated using historical data. The consequential approach considers marginal and major changes to a system, whether this change occurred in the past, present or the future (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. Once the approach is selected 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.

An initial requirement of the methodology is to select the correct approach for the service or product that is to be investigated. The most common approach is a process based attributional LCA and typically this type features four different phases: Goal and scope definition, Inventory Analysis, Life-cycle Impact Assessment and the Interpretation of the results. A process based attributional approach implements its core analysis from database or industry data to quantify the amount of energy or CO_2 required to produce a product or service (Rebitzer et al, 2004; Finnveden et al, 2009; Higgs et al, 2010). In relation to the development of EnvFUSION, the desired approach must incorporate a functional unit that is able to measure a variety of emissions from different sources using a range of various values. Figure 4.3 over the next page illustrates the process based LCA.

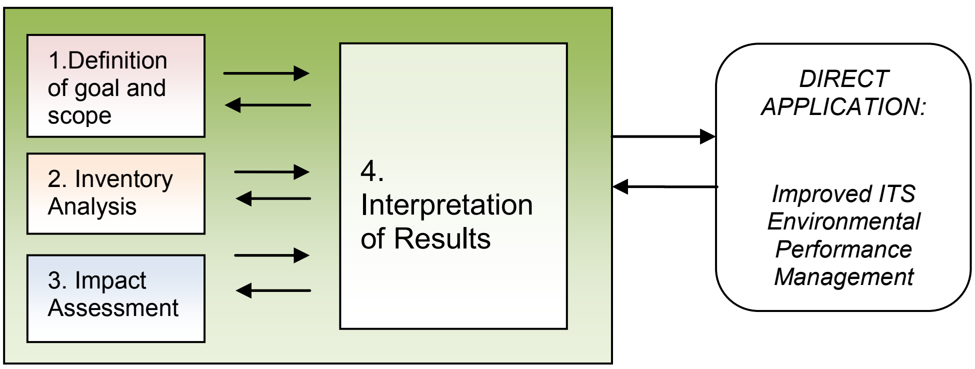

Figure 4.3: - Standard Phases of Lifecycle Assessment

Focusing upon the impact assessment, a further 7 steps can be defined according to Ahlroth (2011) which are: -

- Selection of impact categories, indicators and models
- Classification. A qualitative step where the 'interventions' (inflows and outflows) contributing to each impact categorie are described
- Characterisation. The models chosen are used to quantify the contribution of the different interventions to the different impact categories.
- Normalisation. Here the results of the evaluation are compared against a number of reference values, for example, the total contribution to the impact category for a country.
- Grouping/ranking. A qualitative evaluation.
- Weighting. Here the results of the characterisation or normalisation are weighted against each other with quantitative weighting factors.
- Data quality analysis (Uncertainty Modelling, Sensitivity Analysis etc)

Using a process based LCA, Measurements of ICT road infrastructure must also provide the same accuracy as an estimation of emissions from a vehicles power source. The main advantage of this approach is its simplicity and ease of use. The EnvFUSION framework will be witnessed to increased clarity and improved understanding in relation to the dissemination of the results. However, disadvantages include input 'black spots' where data may be missing or unavailable. Very complex manufacturing processes may therefore lose a lot in the interpretation of the lifecycle results.

> *"A process-based analysis is typically limited by what is commonly referred to as 'truncation' in which some facets of the process that contribute to energy and CO_2 impact are not accounted for in the analysis." (Higgs et al, 2010)*

Another approach is an economic input-output (EIO) LCA which attempts to deal with the limitations of the process-based analysis via estimating CO_2 and energy emissions based upon their economic value. Other approaches attempt to combine the EIO and process based models in order to gain advantages of both. For example, a hybrid model from the perspective of ICT manufacturing which uses high-purity chemicals is given a multiplier based upon the economic value of the materials (Williams, 2004), A Hybrid Life-Cycle inventory of nano-scale semiconductor manufacturing (Krishnan et al, 2008) was developed including a library of typical gate-to-gate materials and energy requirements, as well as emissions associated with a complete set of fabrication process models used in manufacturing a modern microprocessor. Their results provided a comprehensive data set and methodology that may be used to estimate and improve the environmental performance of a broad range of electronics and other emerging applications that involve nano and micro fabrication.

The majority of life cycle inventory (Attributional LCI) studies assume that computation parameters are constants or fixed functions of time (Ekvall and Andrae, 2006). Consequential Lifecycle Assessment (cLCA) is a relatively new method that has arisen in the past 20 years and has been developed in order to forecast the marginal and dynamic changes in a product system, pushing beyond physical relationships in the lifecycle inventory using supply, demand and market variables (Sandén and Karlström, 2007; Earles and Halog, 2011; Chen et al, 2012; Zamagni et al, 2012). Its origins came from an initial desire to merge economic and traditional LCA modelling approaches which traditionally relied on Partial Equilibrium (PE) which is based on only a restricted range of market data. The integration of other economic behaviour into cLCA, such as rebound effects and experience curves has been the focus of later research. Since economic modelling traditionally plays a primary role in decision making it has since became a popular yet versatile method to implement advanced forecasting studies. This is due to the method no longer focusing solely on economic integration but its ability to identify key marginal or revolutionary sustainable and socio-technical processes within a system.

According to the literature, cLCA is a method that is still maturing. There is ambiguity in its structure as it features no standard methodology with opinion being split on what it should achieve. Its function varies depending on its application, identification of processes included is often done inconsistently using different arguments which leads to different results. Zamagni et al (2012) suggest that the 'logic of mechanisms' could act as a supporting framework in determining whether an LCA or cLCA should be suitable if not both. Going further, this logic could also be extended, considering cLCA as an approach rather than as a modelling principle with defined rules to increase its versatility. An additional modelling tool would therefore need to be applied that supports the key features it aims to provide. It should in fact be noted that System Dynamics Modelling (SDM) could offer a suitable platform in order to model the consequences due to its ability to handle variables through time (Shepherd et al, 2012; Stasinopoulos et al, 2012) and was presented as a tool for providing decision support to transport policy makers (Schade and Rothengatter, 2001). SDM is a tool able to handle a high complexity of interactive subsystems so that it is appropriate for analyzing long-term impact mechanisms within the transport sector and between the transport sector such as ITS and other sectors of the economy (Schade et al, 2003). ITS systems could be evaluated via the creation of a forecasting methodology across a macroscopic perspective, integrating previously isolated focal systems such as IT infrastructure, vehicle operation and the production and disposal of road-side infrastructure. Considerable debate about the use of various weighting methods has emerged within LCA research.

According to Ahlroth (2011) some methods that were crafted during the 1990's are still in use today. Such examples include the EPS (Environmental Priority Strategies) method which is based upon a monetary approach and is an endpoint method (Steen, 1999). Ecoindicator 99 is also an endpoint method but is based upon a panel approach. Distance-to-target methods like EDIP and Ecoscarcity can be used to evaluate different environmental impact categories depending on the distance between a current level of environmental pollution and a future environmental target value, allowing quantitative weightings to be applied to estimate performance (Seppälä and Hämäläinen, 2001; Lin et al, 2005; Weiss et al, 2007).

More recent methods focus upon the midpoint (impact phase). Examples include Ecotax and BEPAS, both methods are based upon monetary valuation of midpoints. According to Finnveden et al (2009) recent developments have focused a great deal upon improving the methodology of LCA. For instance, the *goal and scope* stage can be defined differently when taking into account either attributional or consequential approaches. For the inventory analysis, this is relevant when discussing system boundaries, data collection and allocation. According to Hunt et al (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. It is assumed for the purposes of this research that this type of simplification is not recommended as the weighting and results will differ too substantially from those that would have been produced using a more detailed analysis, particularly when the output is subject to aggregation when combined with other tools such as Multi-criteria analysis, Cost-benefit analysis etc.

Whilst being a popular and effective assessment tool, both approaches also carry some limitations. The simplified variant tends to be insensitive to geographic aspects. For example, the product process which is based upon time and space is aggregated to a point which doesn't reflect the geographic location of the individual emissions (Ossés de Eicker et al, 2010b). 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 both LCA approaches 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). Impact results typically lack the duration of emissions as well as their concentration. Finally, the functional unit of an LCA consists of a very small assessment space. Various emissions are given a proportional share of the full emissions from each stage. The LCIA must operate on mass loads representing the share of the full emission output from the processes.

To the best of the authors' knowledge to date no LCA studies for inter-urban ITS schemes have been published. Several studies have been investigated from the microscopic perspective focusing on renewable energy (Mathiesen et al, 2009), material replacement (Stasinopoulos et al, 2012), vehicle emissions and ICT products (Higgs et al, 2010). Within the transport sector, studies have focused 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).

According to Higgs et al (2010) a great deal of effort has been made recently in an attempt to define the whole lifecycle of energy production and CO_2 impact of ICT as well as the materials that are used in the manufacturing process. Although the main issue is a lack of inventory data for high purity or speciality chemicals (Spielmann and Scholz, 2005; Krishnan et al, 2008). 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. Determining the energy and carbon emissions while the product is in use is a challenge due to the almost infinitesimal configurations of equipment (Stobbe et al, 2009; Dao et al, 2011). This is important, as an Economic input output LCA often concludes that embedded energy contributes a larger portion of lifecycle energy and CO_2 impact compared to process based LCA's which argue that product use is the largest contributor. Calculating the levels of energy and CO_2 within the IT supply chain is even more complex.

> *"The lifecycle contribution from product use requires making assumptions about typical product use patterns (e.g. hours per year each PC spends in active, idle, off, etc. modes) and also about expected product lifespans." (Higgs et al, 2010)*

Evaluation of LCA's expected contribution to EnvFUSION			
Advantages	**Positive Indicator**	**Disadvantages**	**Negative Indicator**
Clearer environmental benefits which may reveal emissions hotspots so that a redesign of the product or service can take place.	High	Data collection may be extensive and may delay the analysis of impact assessment.	Seldom
Cost reduction when using a simplistic LCA process allowing quick results via Ecoinvent.	Very High	A full LCA may also be expensive to carry out due to the above and also may suffer uncertainty due to the lack of sufficient data.	High
Cost reduction and easier access to product development funding for conducting a lifecycle in transport.	Very High	Calculating the Lifecycle of ICT Hardware/Software difficult due to a high variety of equipment and lack of inventory data in the materials used.	High
Can provide consequential forecasting facilities which illustrate dynamic changes in the focal system in addition to supporting exogenous variables.	Very High	Lack of a standardised methodology for conducting consequential lifecycle assessment.	Low

Table 4.7: - Evaluation of Lifecycle Assessment

It appears that estimating ICT emissions at the product level would be unfeasible for this research study. Instead, it may be more useful to develop general criteria which reflect the operational performance of the ICT data links using metrics that are readily available. Due to ITS involving a combination of ICT and transport related concepts, it seems advisable to articulate the process around quantitative and non-monetary data values. Overall, the Lifecycle assessment offers a very promising method for estimating emissions throughout the various stages of ITS schemes. The attributional approach is feasible for estimating the emissions of current ITS schemes using a fixed inventory while the consequential approach (along with a suitable forecasting platform) can be used to estimate the emissions of future technologies in the planning stage or a longer time frame. Table 4.7 illustrates the expected contribution to the proposed framework.

4.3.7 Regional/Strategic Environmental Assessment

A strategic environmental assessment is based upon a form of sectoral policy analysis and assessment. It has gained significant popularity from the start of the 21st century. Born from limitations within the methodological framework of EIA and an ever increasing requirement to deliver environmental assessments from a strategic (holistic) or regional perspective, the development of SEA has grown into an internationally recognised framework in its own right (Ahlroth et al, 2011). Environmental, social and economic policy comes under scrutiny and moves far beyond the motivations for new policy development. The application of SEA can be perceived from the local, regional or national levels. It is therefore the first 'sectoral' ESAT model featuring a holistic perception of the environment compared to a typically localised assessment. A top-level and prioritised level of assessment was therefore initiated. Early examples of SEA projects according to Jay (2010) include an analysis of clean coal technologies in the USA and to determine the environmental significance, an assessment of a Swedish municipalities energy plan commenting on the environmental issues associated with energy use and finally, a study for local wind farm development in Germany consisting of mapping environmental criteria restricting the location of wind farms and assessing the impacts of farms in favoured areas.

Environmental side-effects and reactive scenarios of broad development strategies are to be decided before the individual projects materialise. This 'screening' process envisages that projects must be in line with environmental strategies (where applicable) otherwise they will get cancelled or declined. In other words, SEA aims to overcome the weaknesses in EIA via up-streaming the processes of environmental assessment to a higher strategic level of decision making. Originally, SEA would be carried out at three levels of planning with policies, plans and programmes forming a vertical hierarchy (Wood and Djeddour, 1992). EIA should therefore focus upon the finer details of planning and the scaling of project proposals as already specified within the legal guidelines of the SEA.

> *"The principle remains that an SEA process should run alongside the preparation of a strategic planning action, and ensure that environmental issues associated with the action are carefully assessed before project- level planning begins. (Jay, 2010)*

Jay (2010) argues that SEA has received very little reception with regard to its use within the energy sector despite its advantageous strength to improve project management at the top tier of planning. In relation to low carbon transport and ITS there has been no real application that addresses the criteria within this specific model from the perspectives of organisations such as road network operators. EIA has become an established practice when developing energy infrastructure for example, determining the location of power stations and energy infrastructure such as pylons and transformers etc. More recent developments within the energy sector involving SEA is shown in Table 4.8 and is adjusted from a review by Jay (2010).

Energy sector project groups	Individual project descriptions
Individual Energy Technologies	Bio energy expansion in China (Owens, 2007). Carbon capture and storage schemes in the Netherlands (Koornneef et al, 2008). Assessment to facilitate development of a regional renewable energy strategy (Brooke et al, 2004).
Offshore Energy Resources	Ongoing SEA process over several years for exploitation of offshore energy resources (Sheate et al, 2004). Exercises for North Sea oil and gas exploration licensing and offshore wind energy combined in unified approach to marine energy resources (Department of Energy and Climate Change, 2009b). Ireland conducting SEA for offshore hydrocarbons exploration (Department of Communications, 2011). SEA carried out in USA for energy development in Gulf of Mexico (Environmental Protection Agency, 2011). Offshore oil and gas exploration in Canada (Noble, 2009). Holistic environmental assessment of UK offshore oil (Salter and Ford, 2001).
Grid Systems	Within the EU, a variety of operators of large-scale electricity grid systems have begun to implement SEA for development in order to follow legislation derived from the EU SEA directive. Examples include Belgium, Italy (European Commision, 2009) and Portugal. A UK grid operator has gained voluntary experience in the form of upgrading the regional network. Alternative solutions were presented that would have become missing in the detail of other assessment methods such as embedded generation (Marshall and Fischer, 2006). Finally, CIGRE (International Council on Large Electric Systems) has incorporated SEA into discussions on environmental performance (Jay, 2010).
Planning Guidance	There is a growing interest in SEA practice within spatial planning guidance. This could have repercussions on the improvement and implementation of energy infrastructure. Research is saturated with examples and are too numerous to get an accurate benchmark for generalisation. Some examples will have included energy case studies within their research. Energy production may be determined by planning frameworks. In the UK draft planning guidance for energy production has been delivered through a broad sustainability appraisal process (Department of Energy and Climate Change, 2010).
National Energy Policy	Using a combination of scenario analysis to explore the likely effects of contrasting energy mixes and a more potent levels of energy conversion for entire countries or sectors. Developing countries have implemented these techniques in addition to countries in transition. Examples include Czech and Slovakian Republics and Pakistan (Dalal-Clayton and Sadler, 2005). Canada has also explored various energy studies (Noble, 2009) as well as Iceland (Thórhallsdóttir, 2007). Finally, South Africa's national energy utility has applied an SEA process to merge environmental issues into their overall operations (Retief et al, 2008).

Table 4.8: - Energy Project Groups and Descriptions

It is argued that the EIA assessment comes into play too late within development proposals to be considered as a useful tool as momentum has already increased and certain decisions (location, resources, land use etc) have already been approved by this stage. For example, a proposed power station in the UK did not include the implications a grid upgrade would have upon the environment (Sheate, 1995). The influence only covers improvement of separate individual projects. Energy and transport (or a combination for Intelligent Transport) need to be resolved from a higher level of planning, therefore an SEA is designed to tackle issues from a strategic perspective. In addition, EIA's focus on solitary projects gives it a significant disadvantage in assessing decisions from multiple projects, hence the holistic perception.

A number of ITS services such as Active Traffic Management and more advanced technologies consist of the construction of infrastructure at multiple sites, therefore SEA seems to overcome the weaknesses in EIA's lack of support for ubiquitous technology implementation. In a case study in Finland Pölönen et al (2011) suggested that the main problem of Finnish environmental legislation was that the consequences of environmental negligence within projects were assessed within the limits of localised permit statutes. In other words, a localised approach made it difficult to consider various environmental consequences holistically. The Finnish EIA act was the first Finnish environmental statute that identified the need for a thorough assessment of environmental impact. In addition the social aspect has been enhanced due to increased participation of the Finnish public. The level of environmental information also increased so that the public can take part in any future project that will have direct implications on environmental properties. Although the author does not mention SEA, it is clear that the move to a holistic perspective indicates a change in the vantage point of environmental perception to a broader picture, which allows earlier planning with sustainable projects being given a greater priority with improved social enrichment.

Most SEA approaches suggest valuation to ensure a successful decision making process of the confirmed choice and alternatives. This is due to the lack of suitable weights being available for this model. According to Ahlroth (2011) SEA has not been institutionalised or standardised, although various documents that acknowledge the tool should be strengthened and integrated into national standards have been available for some time. The European Union is one example (European Commision, 2003).

> *"Across the European Union, for instance, a directive on the assessment of certain plans of programmes has been in place since 2004, but implementation has been piecemeal and slow at the national level". (Ahlroth et al, 2011)*

Environmental security must be infused into energy and transport frameworks at an earlier stage of conception. Ironically, organisations adopting the SEA framework have produced considerable infamy lacking the 'strategic' aspiration of high level planning and integration as no in-depth assessment is carried out. Sánchez and Silva-Sánchez (2008) carried out a case study into highway planning on São Paulo's (Brazil) heavily urbanised metropolitan region. The agency in charge commissioned an SEA of a revised project naming it the Rodoanel programme. The SEA report produced failed to successfully document significant strategic issues. The concerns were related to the detrimental consequence of inducing urban sprawl over a designated water protection zone and therefore acted as a major hurdle to project licensing.

According to João (2007) an SEA succeeds depending on its ability to integrate the environment into a strategic decision making process relying on the selection of both data and scale. Therefore the first major question that is encountered is should data collection come first or the identification of key issues? Project managers appear to misinterpret what the SEA attempts to accomplish. Another argument is that due to resource restriction and financial limitations only a limited amount of data collection could be implemented at each stage of the decision making process.

> *“Not all the baseline data must be available for an SEA to proceed. The first SEA can be seen as a way of identifying what needs to be monitored in the future” (Therivel, 2004, p. 38)*

Due to the limited resources available, a selective data collection method would need to be carried out that focuses on the 'sensitive' data that is relevant to the identification of significant environmental impact (Seht, 1999, p. 6). Figure 4.4 illustrates the individual stages an SEA will take in order to assess sustainable projects or higher legislative policy.

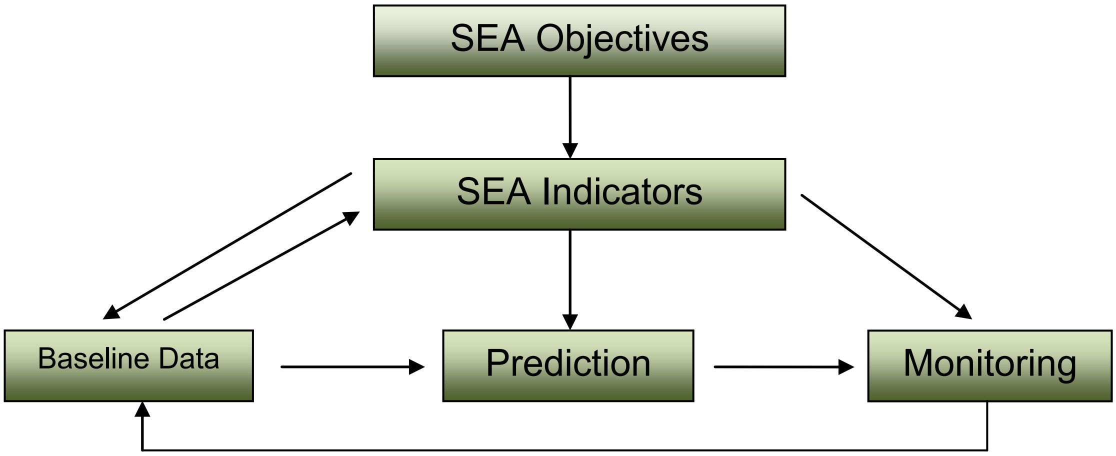

Figure 4.4: - Links between SEA objectives, indicators and baseline data (Source: Therivel, 2004)

Table 4.9 illustrates the proposed contribution to the EnvFUSION framework.

Evaluation of SEA's expected contribution to EnvFUSION			
Advantages	**Positive Impact**	**Disadvantages**	**Negative Impact**
Improves project management at the top tier of planning	Low	No significant measure to enforce strategic assessment in the early stages which is contradictory to what the framework is trying to achieve	High
Can estimate environmental performance at multiple sites thus relating such performance between the road infrastructure and the regional data center.	High	Lack of suitable weights available for the model means economic valuation is recommended .	Very High
		High level of data collection involved as well as knowledge of sectoral environmental awareness	High

Table 4.9: - Critical Evaluation of Strategic Environmental Assessment

4.3.8 Transport-based Environmental Frameworks and Network Simulation Models

This section discusses sustainable frameworks and network simulation models particular to the transport field.

Various frameworks based upon a UK perspective have been proposed in the literature. May et al (2008) as part of a 4 year research programme known as DISTILLATE proposed a set of decision support tools for urban based transport for use within local governments and is derived from the use of surveys and case studies. They argue that no other research that currently exists provides a more detailed approach to tackling barriers to sustainable transport than the methods documented within their research. Brand et al (2012) developed a strategic transport/energy/environment model known as the UK Transport Carbon Model (UKTCM). The model is a disaggregated bottom up transport model of energy use and lifecycle carbon emissions based upon a UK perspective. It provides annual projection of transport supply and demand. Current models that have been developed to map the Transport-Energy-Environment (TEE) system assume that society is based upon a static value that never changes. According to Brand (2012) three approaches have been developed in Europe. Top down optimisation models include PRIMES and MoMo (Syri et al, 2001; Fulton et al, 2009), bottom up simulation models include TRENDS and TREMOVE (Georgakaki et al, 2005; Schäfer et al, 2006) and finally, transport network models that analyse the flow of the network (emissions, etc) have been developed such as ASTRA, SCENES and EXPEDITE (De Jong et al, 2004). The current models explore specific policy questions but seem to lack the bottom-up sectoral approach required in order to acquire the integrated supply and demand side strategies to reduce carbon emissions. In addition, they do not seem to cater for the full lifecycle of GHG emissions.

> *"We will not achieve a low carbon transport system without a combination of demand management, operational, pricing and technical policy options" (Brand et al, 2010)*

Diaz and Garcia-Navarro (2010) proposed a methodology for an indicator of energy applied to inter-urban road transport. The current methodology presents criteria which standardises aspects of current environmental and socio-economic complexity. The proposed methodology introduces an indicator which will measure the whole lifecycle of embodied energy usage within the UK's highways. The indicator is designed to interconnect to other sustainable indicators for increased accuracy and fullness of the data that is produced from the energy and emissions analysis. The motorway is treated from different perspectives to produce the lifecycle assessment. Several stages to be assessed include the construction and material usage in highways such as tunnels, infrastructure and toll facilities. Also, the energy that is utilised through the management, maintenance of the infrastructure elements as well as the energy consumption of vehicles that use the highway. Finally, the energy transfers incorporated in the demolishing, negation and restoration of the total landmass highway previously occupied is assessed.

Ülengin et al (2010) proposed a methodology for a decision support framework that assists policy makers in the evaluation of strategic transport related decisions. The framework uses various methods, including a Structural Equation Model (SEM), scenario analysis and Multi Attribute Decision Making (MADM). The methodology features three distinct stages. The first stage consists of utilising a cognitive map for understanding experts' key opinions on the relationships between transport and the environment. An SEM is then synthesised from the cognitive map. This allowed the framework to quantify the relations from external transportation and environmental factors. Finally, the results of the SEM model are used to evaluate the consequences of possible policy using scenario analysis. Ülengin et al argues that in order to achieve a sustainable transport system, the interaction of the relationships between transport and the environment must be considered.

4.4 Managing Uncertainty in ITS Sustainability Modelling

It is apparent from the critical review of methods in the earlier sections typically in environmental and socio-economic reporting that uncertainty exists throughout the environmental modelling of inter-urban transport projects. ITS however, offers a unique set of problems which current transport appraisal techniques will ignore. This uncertainty can be broken down into various perspectives.

4.4.1 Perspectives of Uncertainty

Firstly, the environmental impact is not limited to the road-side but exists in multiple locations. Referring back to Section 4.3.4 in the example of applying an EIA assessment to Active Traffic Management, most methods tend to focus only on estimating emissions at a localised area. However, the road infrastructure is controlled via several ICT data links which are controlled by an offsite regional traffic control centre. Without the data center the road-side systems that provide guidance and enforcement to drivers would be inoperable, therefore the emissions and energy of the systems linked to the scheme should ideally be taken into account. It is therefore important that the system boundary is expanded to focus on the system, as opposed to the geographical location, to provide a more concrete representation of ITS performance.

The second major form of uncertainty focuses upon the data collection and is based upon the completeness, accuracy, age, geographical source and availability of data (Frischknecht and Rebitzer, 2005). Exploring the ATM example further, the contribution of the environmental impact share of the systems within the data center allocated to the road-side infrastructure must be taken into account. Ideally, this would begin by estimating energy and emissions performance at the software level (the efficiency of the algorithms and source code within the application that operates the ITS schemes). The next level of allocation is the energy requirements of the hardware (physical electronic equipment) that runs the application. It should be noted that estimating the energy consumption of software is very high on the research agenda and represents the most recent research in the Green ICT field (Capra et al, 2012).

> *"The availability of increasingly efficient and cheaper hardware components has led designers to neglect the energy efficiency of software, which remains largely unexplored." (Capra et al, 2012)*

Currently, this poses considerable challenges due to the metrics and monitoring equipment not necessarily being available. The current literature does not even provide software energy efficiency metrics. Not surprisingly, over 50 ISO software quality parameters do not include energy efficiency (Czarnacka-Chrobot, 2009). Although the literature on embedded software energy efficiency is vast (Vahdat et al, 2000). Previous research by Benini and Micheli (2000) focused on improving software efficiency which in turn reduces CPU usage. Capra et al (2012) developed a measure of energy efficiency that is appropriate for software applications. Their findings indicated that a greater use of application development environments specifically, frameworks and external libraries is more detrimental in terms of energy efficiency for larger applications than for smaller applications. They also found that different functional application types have distinctly different levels of energy efficiency, with text and image editing and gaming applications being the most energy inefficient due to their intense use of the processor. If an assessment cannot take place at the software level, then the data center should be assessed at the next level of aggregation which would focus upon the hardware, thus introducing uncertainty due to the CPU also being assigned to tasks that do not relate to the management of ITS services.

The third form of uncertainty is the subjective opinions of multiple stakeholders. It is known that the transport field is one of the hardest areas to decarbonise, it is argued that these difficulties may be due to the variety of stakeholders within the field that tend to give conflicting appraisal decisions and targets (Awasthi and Chauhan, 2011; Awasthi et al, 2011). This level of conflict must be managed in a formal process that can produce logical conclusions based upon all stakeholder involvement.

4.4.2 Methods to reduce uncertainty

In terms of estimating the quality of data, some methods such as LCA as described earlier use extensive databases that feature product processes, the most popular being Ecoinvent. This database features its own uncertainty method known as 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). When using Ecoinvent, the EnvFUSION framework could include a Monte Carlo analysis using uncertainty data from the ELD method (Goedkoop et al, 2010). Uncertainties could be handled consistently using a Petri matrix originally developed by Weidema and Wesnæs (1996).

The uncertainty in the decision making process can be handled by a variety of methods and algorithms that offer decision support capability and such methods are also widely used in the field of artificial intelligence. Data methods based upon the Bayesian theory of subjective probability include Dempster-Shafer theory which allows evidence to be combined from multiple sources with missing data to give a decision. For example, Awasthi and Chauhan (2011) combined DST with AHP in order to estimate the sustainable performance of car-sharing. The main strengths of this approach lie in its ability to treat heterogeneous, uncertain and incomplete data originating from multiple information sources. By combining MCA with fuzzy logic theory (Zadeh, 1965; Zadeh, 1986) new methods have been developed like Fuzzy AHP (Kahraman et al, 2003) and Fuzzy comprehensive assessment (Tao and Xinmiao, 1998). Other methods include the field of possibility theory which can be considered an extension of fuzzy sets and fuzzy logic.

4.4 Relational Comparison of Sustainability Modelling

According to Ahrloth (2011) there is a distinctive need for a set of generic weights which can help to harmonise, increase validity and provide cohesion within the various ESAT tools available. This is of high importance when joining methods in order to share their output and is the approach which would be adopted to estimate the performance of ITS. This can be achieved because there is a large degree of overlap between various frameworks at different levels. Due to the sheer number of weights and combinations it would prove very complex to attempt to map all of the possible relationships that are available. These relationships are discussed in the following sections. A large body of work has focused on the development of sustainable indicator sets in order to assess the changes in transport over a fixed period. According to Gudmundsson (2003) there is a large gap between sustainable indicators and indicator systems currently in use. This argument, in other words, relates to the lack of current metrics that will measure sustainable ideals using a system that will enforce competent decision making. According to Wallis et al (2011) great effort has been produced at the local, national and international levels to select and evaluate various indicators and implement indices in order to further progress within sustainable development. Over 800 sustainable indicator activities have been listed within the compendium of sustainable development indicator initiatives (International Institute for Sustainable Development, 2011).

> *"Indicators are seen not only as means to collect and collate information about the sustainability of social, economic and biophysical systems with the view to better inform decision making and policy formulation, but also as a means for communicating sustainability." (Wallis et al, 2011)*

There is currently a very high opinion that indicators can become useful for progressing sustainability. However, opinion is divided on which indicators should be used for varying roles. There are currently no indicator sets that give universal approval, mainly due to the overall definition of sustainability being vague and ambiguous. This has resulted in the development of a large body of sustainable indicator development due to the underpinning theory bearing little weight. Indicator sets are essentially isolated social and economic data values that have been tied together with environment reporting that bear no relational significance between them (Wallis et al, 2011). The sustainable assessment field is still in its early stages of research with several models being proposed.

4.4.1 Strategic/Sectoral Frameworks

At the strategic level various frameworks exist which provide a measured assessment of environmental management from a top-tiered sectoral viewpoint. These frameworks may use a combination of ESAT tools or models to evaluate the sustainability aspects of large scale generic projects. At this level the frameworks arguably do not share a direct relationship with the weights but they select a range of method groups that contain various forms of weighting and valuation. Table 4.10 over the next page displays the characteristics of each of the strategic frameworks grouped into its name, the users, the study object and the weighting of environmental aspects. In addition, the characteristics of values and weights are shown from Monetary, Non-Monetary, Midpoint/Endpoint and finally generic or specific weights that are applied. The author introduced EnvFUSION to be defined at the sectoral level as it will consist of a number of integrated lower level methods and is highlighted in green.

4.4.2 Tool/Method Level

At the tool or method level, a variety of ESAT tools exist which are dedicated to assessing environmental sustainability from contrasting perspectives. The tools utilise a significant amount of varying weights and methods and depend upon the nature and rationale of the tool methodology. The following table analyses the various methods available as well as the local weights and methods within the environmental management hierarchy.

Sectoral /Strategic	**Users**	**Study object**	**Weighting of environmental aspects**	**Characteristics of values/weights**		
				Monetary/Non monetary	**Midpoint/ Endpoint**	**Generic or specific weights**
SEA	Policy Makers, Public Sector Agencies	Projects, Policies	Optional	Both	Both	Generic (Primarily)
UKTCM	Policy Makers, Governmental Agencies	Transport Projects and Policy	Optional	Both	Both	Specific
EMS	Companies, Agencies, Organisation	Managemen t. of Organisation	Required (Significant Impacts)	Non-Monetary (Primarily)	Both	Generic or company specific
SEEA	Policy Makers, Government Agencies	Policies, Nations, Regions, Sectors	Optional	Monetary	Both	Both
EnvFUSION	*Policy Makers, Government Agencies*	*Policies, Nations, Regions, Sectors*	*Optional*	*Both*	*Endpoint*	*Both*

Table 4.10: - Characteristics of Strategic/Sectoral frameworks and values/weights used

CBA is designed for users such as policy makers and public sector agencies and focuses upon projects and policies. The weighting of environmental aspects is required using a monetary weight format. Endpoint weights are preferred although midpoints are compatible with this tool. The use of generic or site specific weights are also supported. LCA users include the former, plus companies that would carry out an LCA assessment either internally or externally within a site specific location. Objects of study include products, production systems and policies. The weighting of environmental aspects is optional and both weighting formats (monetary, non-monetary) are allowed. Midpoint and Endpoints are used and only weights developed specifically are compatible with this tool. LCCA although similar to CBA due to its valuation methods features a different configuration in terms of specification. LCCA is designed for companies and public sector agencies and its study object features products and production systems. The weighting of environmental aspects is optional and like CBA it is focused upon a monetary value format. Both midpoint and endpoints can be utilised and the tool supports generic and specific weights. ERA is designed for policy makers, public sector agencies and companies. Study objects include projects and production systems and the weighting of environmental aspects is optional. It features monetary costs in relation to avoiding and recovering from failures by identifying the risk. It prefers the use of endpoints and supports both generic and site specific weights. The methods that were selected for EnvFUSION due to possessing the highest benefits in the previous section are highlighted in Table 4.11.

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

Table 4.11: - Characteristics of Tool/Models and values/weights used

4.4.3 Weighting Methods

Each of the methods described above feature varying sets of weights and although they are to a large extent overlapping, the classifications used are based on different rationales, and none of them cover all types of methods (Kopp et al, 1997; Finnveden et al, 2002; Hanley et al, 2002; Mishra, 2003). Table 4.12 illustrates the characteristics of the weights applied to their parent method, a brief description and their relevance to the proposed study, (0) indicating the method is completely out of scope, (*) meaning some minor elements such as values of weighting approaches could be adopted, (**) is where major elements can be used and the majority of the weighting approaches can be explored and finally (***) is where the method is completely compatible within the scope of the study.

Parent method	Weighting approach	Description	Relevance to the study
Contaminant Transport and Transformation	Various	Deals with the mitigation of hazardous materials which may cause harm if released on the environment. It is out of scope for the study.	0
Distance-to-target Methods	EDIP Ecoscarcity	Enables performance to be estimated based upon the current environmental burden and the minimum value to reach the target. This is very relevant to the study. however, In order to overcome the limitations of the lack of weighting priorities MCA weighting approaches should be adopted.	**
Economic Input-Output	Various Monetary weights depending on scenario	Assists in measuring the economic lifecycle of a product system. This is out of scope for the study due to the lack of economic knowledge of ITS systems.	0
Emergy Analysis	Emergy Met Primary Production	Measures the level of all the direct and indirect energy of the material, services, and information required to make a product or sustain a system. Out of scope.	0
Expert Elicitation	Various	Expert elicitation is the synthesis of opinions of experts of a subject where there is uncertainty due to insufficient data or when such data is unattainable because of physical constraints or lack of resources. Highly relevant to the study due to potential gaps in knowledge and missing data.	***
Exposure Assessment and Dose Response	Various	A dose-response relationship describes how the likelihood and severity of adverse health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided). As the scope of the study focuses solely on climate change impact, this method is out of scope.	0
Panel Weighting Methods	Pair-wise comparison (AHP, ANP etc) Expert Assessment	Panel weighting methods are based upon Multi-Criteria Decision making. They may contain generic weighting assignments which can be considered very useful to the study.	***

Table continues on next page...

Parent method	Weighting approach	Description	Relevance to the study
Process based Impact Assessment (LCA)	CML 2001 Eco-Indicator '99 EPS Ecotax BEPAS	LCA's midpoint and endpoint methods are based upon a process based impact assessment. These methods allow the inventory of a product to be categorised into a number of sustainability areas including climate change (mid-point) and damage categories including impact on local health. The CML 2001 method was selected due to the focus of the study being focused on climate change only	**
Probabilistic Methods	Basic Probability Assignment	Probabilistic methods such as Dempster-Shafer theory can assign belief to certain categories of performance via basic probability assignment. The method would be very useful in combining evidence from multiple stakeholders in order to assist the proposed framework in making a decision.	***
Proxy Methods	Ad-hoc scoring Indicators in Physical Units	Proxy methods are measurements of physical, chemical, or biological processes that depend on the weather, and therefore provide an indication of past climates. They may be used in order to predict future emissions performance of ITS systems and could be useful in providing initial emission estimates.	**
Stress Response Analysis	Various	stress response analysis can be used to evaluate the potential maximum environmental impacts caused by projects before the system fails. This is out of scope due to the focus on climate change only.	0
Uncertainty Analysis	Sensitivity Analysis	Sensitivity analysis can be used in EnvFUSION to test several scenarios including synthetically altering the opinions of stakeholders in order to test the robustness of the framework.	***
Willingness-to-pay and other socio-economic methods	Cost to Reach target Damage Cost Avoided Hedonic Pricing Market Prices Replacement Cost Method *Revealed Preference* *Stated Preference* Substitute Cost Taxes	Willingness to pay (WTP) is the maximum amount a person would be willing to pay, sacrifice or exchange in order to receive a good or to avoid something undesired, such as pollution. The Cost-to-reach target could be allocated within a distance-to-target method in order to expand its functionality while market prices may be used to forecast expected demand of future ITS technologies.	**

Table 4.12: - Characteristics of tool/models and values/weights used

4.5 Summary

A critical review of various ESAT tools has been carried out in order to identify suitable approaches for estimating the sustainability performance of inter-urban ITS and satisfies the second research objective (RO2) of the thesis.

A Sustainability Assessment Hierarchy (Figure 4.5) over the next page was developed which illustrates a graphical overview of the main ESAT models within the Environmental Management field. This maps the most common frameworks with the appropriate method groups and weights that reside within each. Selected methods, models and weights were highlighted depending upon their appropriateness to the EnvFUSION framework. The next chapter consists of the development of the case study and data collection strategy based upon the methods, weights and tools that were deemed to be suitable from the review of ESAT methods.

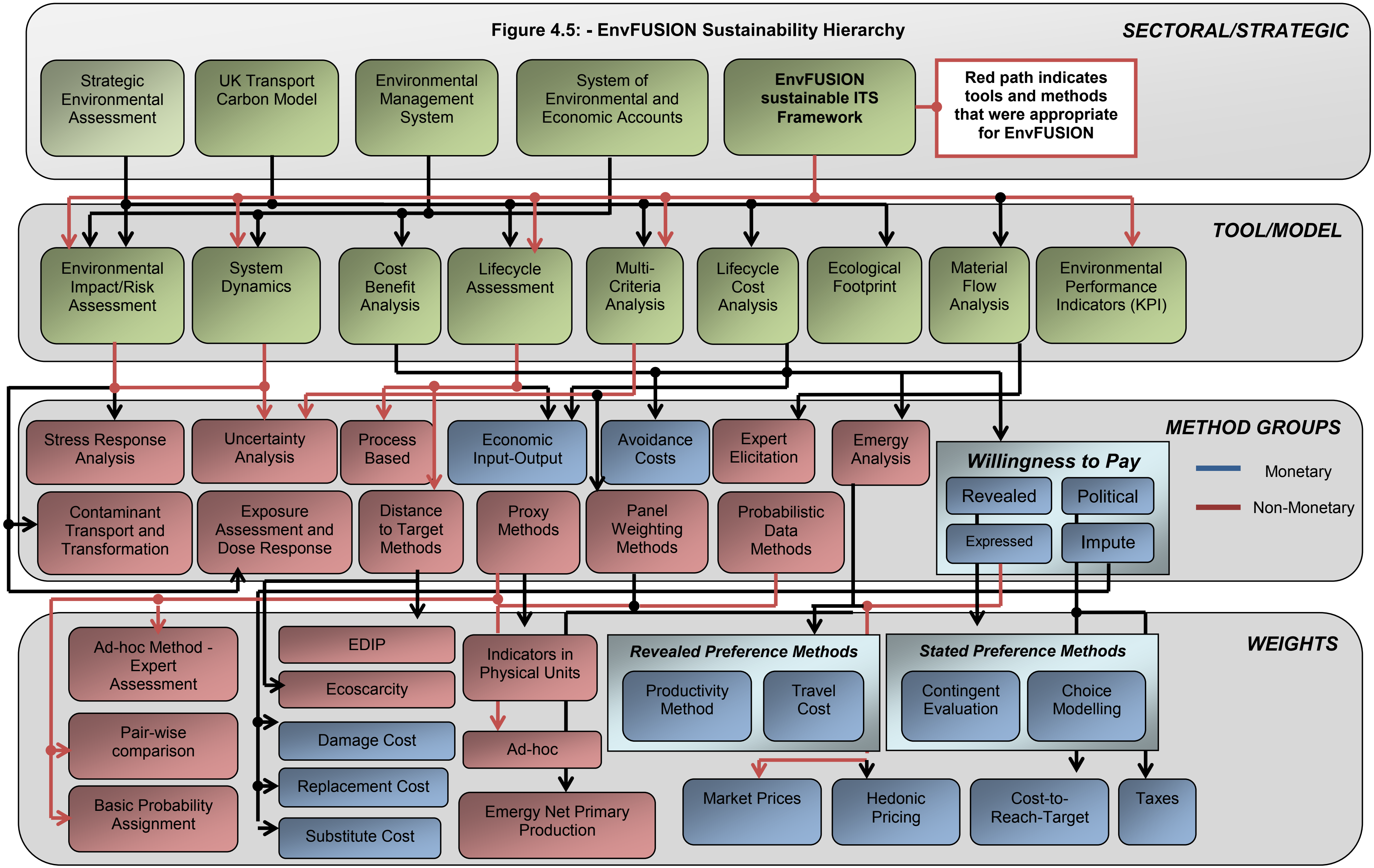

Figure 4.5: - EnvFUSION Sustainability Hierarchy
SECTORAL/STRATEGIC
Strategic Environmental Assessment
UK Transport Carbon Model
Environmental Management System
System of Environmental and Economic Accounts
EnvFUSION sustainable ITS Framework
Red path indicates tools and methods that were appropriate for EnvFUSION
TOOL/MODEL
Environmental Impact/Risk Assessment
System Dynamics
Cost Benefit Analysis
Lifecycle Assessment
Multi-Criteria Analysis
Lifecycle Cost Analysis
Ecological Footprint
Material Flow Analysis
Environmental Performance Indicators (KPI)
METHOD GROUPS
Stress Response Analysis
Uncertainty Analysis
Process Based
Economic Input-Output
Avoidance Costs
Expert Elicitation
Emergy Analysis
Willingness to Pay
Revealed
Political
Expressed
Impute
Monetary
Non-Monetary
Contaminant Transport and Transformation
Exposure Assessment and Dose Response
Distance to Target Methods
Proxy Methods
Panel Weighting Methods
Probabilistic Data Methods
WEIGHTS
Ad-hoc Method - Expert Assessment
Pair-wise comparison
Basic Probability Assignment
EDIP
Ecoscarcity
Damage Cost
Replacement Cost
Substitute Cost
Indicators in Physical Units
Ad-hoc
Emergy Net Primary Production
Revealed Preference Methods
Productivity Method
Travel Cost
Stated Preference Methods
Contingent Evaluation
Choice Modelling
Market Prices
Hedonic Pricing
Cost-to-Reach-Target
Taxes

"The most widely used decision models in ITS evaluation, such as cost/benefit analysis, often do not effectively incorporate value-added or system wide perspectives into their benefit assessment due to the isolated approach to individual capital project evaluations" (Haynes and Li, 2004).

Chapter 5 - Development of the Study and Data Collection Strategy

This chapter discusses the development of the case study and data collection strategy. A method integration strategy was proposed and a large singular case study was designed which features two embedded units of analysis in the form of current and future ITS technology assessment approaches. The aim of this analysis was to estimate current ITS performance bearing the significance of the UK's and EU's legislative targets. The study attempts to analyse ITS service performance using both linear and dynamic scenarios with distinct timescales featuring three different forms of ITS service. This is to demonstrate the robustness of the EnvFUSION framework mechanism. The data collection strategy is illustrated for both types of analysis.

5.1 Overview of the proposed framework

The following sections discuss the development of the EnvFUSION framework as well as the design of the case study. An overview is presented based upon the critical review in Chapter 4 illustrating what the framework should achieve and its model integration strategy to ensure the framework meets acceptable levels of accuracy and cohesion between the methods used. Performance criteria were defined to represent the environmental and socio-economic parameters. The final stage was the data collection strategy which was discussed for each mode of analysis. A case study was then produced which aimed to apply the framework to current and future ITS services on a congested stretch of highway.

5.2 Model Integration Strategy

This section discusses the model integration strategy which illustrates how the relevance of the methods in Chapter 4 were categorised and applied to the framework based upon its key objectives.

5.2.1 Key goals and focus of the proposed framework

The goal of the EnvFUSION framework is to estimate the performance of an ITS technology or service based upon selected environmental and socio-economic parameters and to identify potential areas for improvement. As discussed in Chapter 4, from the critical review it was decided that the focal area was to be assessed based upon the system rather than the sole geographical area, not only from the transport aspect but also from the ICT perspective which includes measurements of ICT infrastructure used to provide the ITS service.

LCA was highlighted in the critical review as possessing suitable flexibility for exploring the production, operational and disposal stages of the ITS services in focus where available. It was assumed that an Attributional approach could be used to assess the current ITS schemes in operation, while a Consequential approach could be used to assess future potential scenarios and services. It should be noted that the operational phase includes the emissions of vehicles although a separate vehicle emissions model would have to be developed which would incorporate the road user flow data of the region as well as the market share of vehicle emissions standards.

Methods must also be introduced in order to manipulate and fuse multiple data sets based upon the subjective opinions of stakeholders. The chosen method was to apply basic probability assignment (BPA's) as discussed earlier using probabilistic data fusion. As well as measuring the efficiencies of transport and ICT attributes, the ITS service itself may offset some of the emissions via increasing efficiency in the transport network. Additional weights from other methods needed to be included in order to prioritise environmental, social, and economic groups. The focus of the study introduced scenarios that work within the UK's CO_2 baselines but were independent of any frameworks or methodologies that currently exist. Such targets need to be incorporated into the performance measurement. Distance-to-target methods provided a promising approach although they had to be expanded in order to take into account not just emissions but also socio-economic criteria. It was decided that the geographical area would be focused upon the M42 highway at junctions 3a to 7 (Figure 5.1).

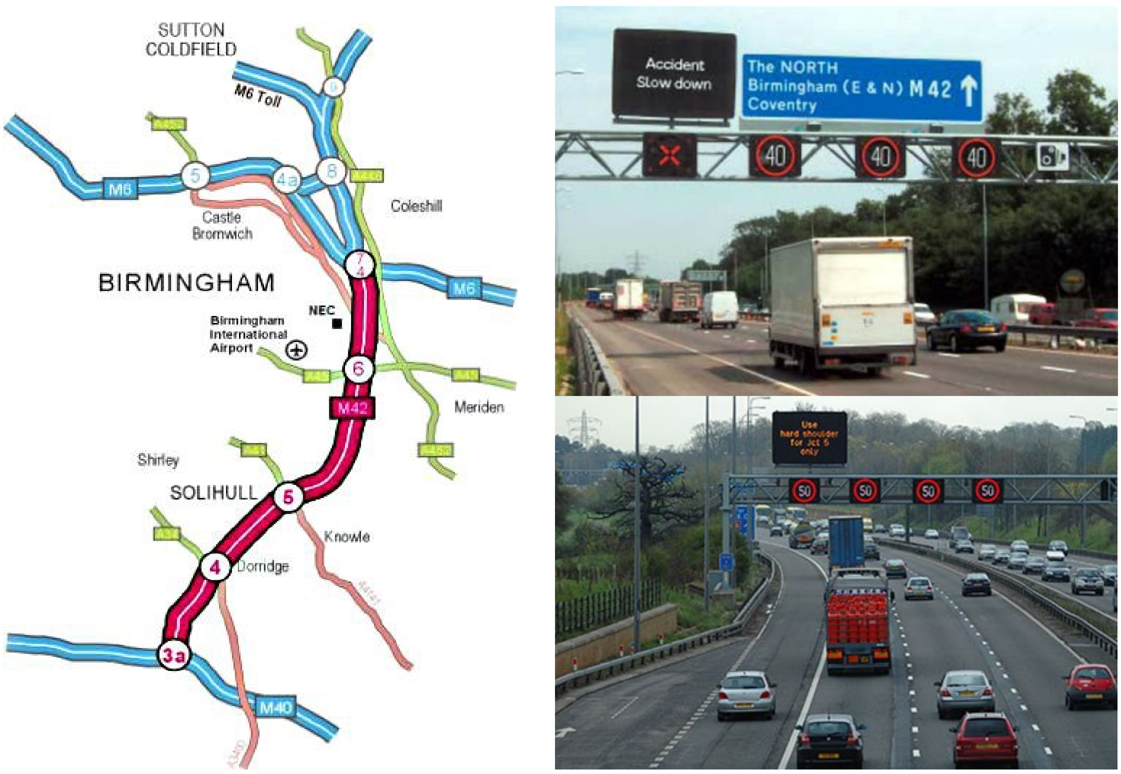

Figure 5.1: - M42 junction 3a-7 traffic corridor near Birmingham city centre

It is one of the most congested transport corridors in England with over 120,000 vehicles passing through daily, acting as a major artery between the north and south of the country as well as serving Birmingham international airport and the logistics of the neighbouring organisations and the National Exhibition Centre. Since 2006, Active Traffic Management has been installed in order to improve rapidly degrading traffic flows. Several benefits have been gained from its usage (Mott Macdonald, 2009; Ogawa et al, 2012). Capacity has increased by an average of 7-9% with 7% of users encountering no congestion in 2007 compared to 2003. Temporary shoulder running has reduced journey times by up to 24% in northbound and 9% in the southbound direction and has increased the average speed by 5 mph (8 kph). Speed compliance has been improved by 94% at 70 mph (113 kph). Safety has improved with the number of personal injury accidents per month reduced from 5.08 to 1.83. Emissions have been reduced while fuel consumption has decreased by 4%.

5.2.2 Method Selection

In order to satisfy the third (RO3) and fourth (RO4) research objectives of the thesis the framework must be capable of estimating performance not just from current ITS services but also future and predicted technologies. Figure 5.2 over the next page illustrates the filtering of the most relevant methods into the current ITS assessment and future forecasting modes, both representing the two embedded units of analysis.

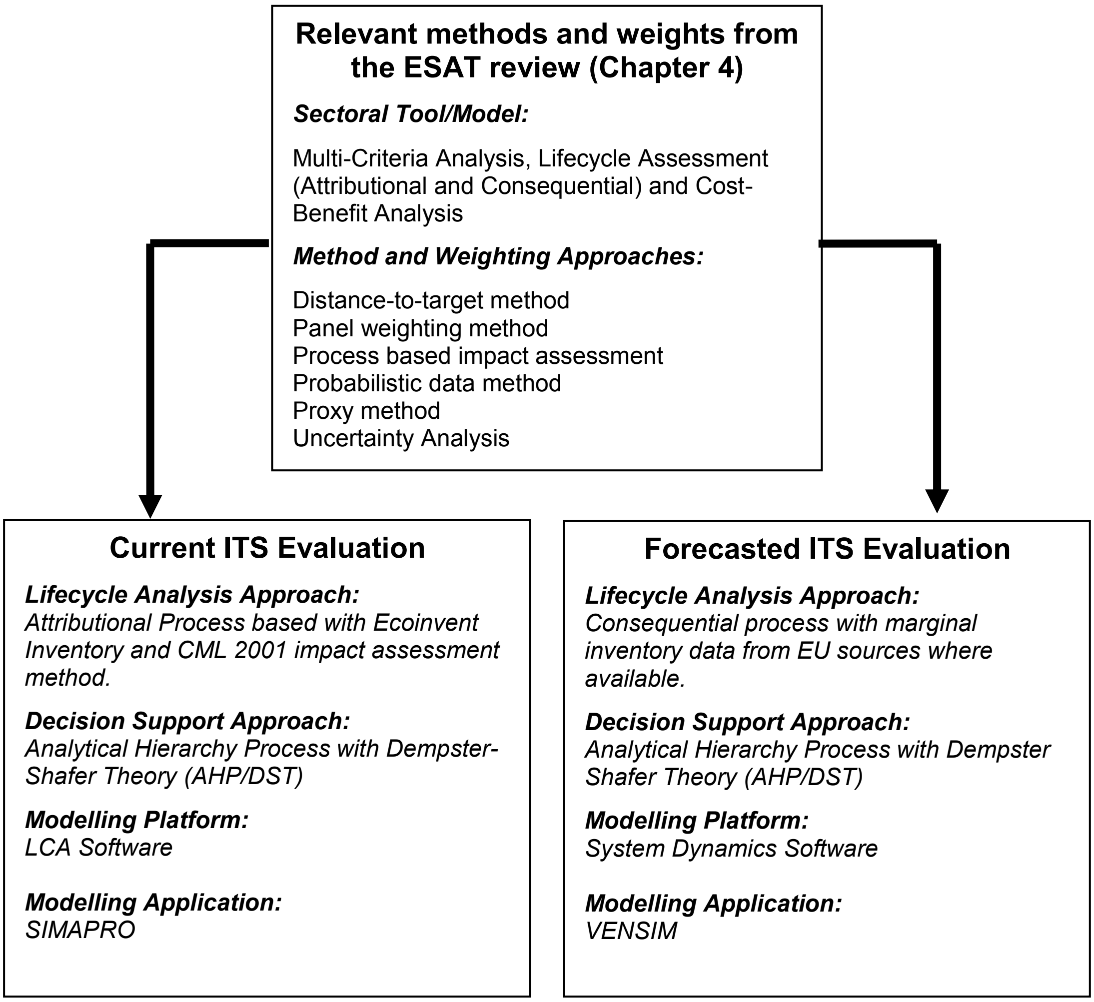

Figure 5.2: - Selection of the methods for current and future ITS Scenarios

An LCA, encompassing an attributional format for assessing ITS technologies that are currently in operation and a consequential approach for technology forecasting was selected. A modified and expanded version of a distance-to-target method proposed by Weiss (2007) and Lin et al (2005) would be used as an additional quantitative performance parameter. MCA methods would enable decision makers that use the framework to rank and prioritise the performance at the environmental and socio- economic perspectives as well as individual criteria. It was decided that the AHP would be selected. In addition, the decision support approach would be augmented via a probabilistic data fusion method. AHP would be combined with Dempster-Shafer theory.

5.2.3 Decision Support and Reporting

For the decision making method it was decided that the EnvFUSION framework would use 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 ITS schemes. The configuration of sustainable performance using Dempster-Shafer theory in this research has been influenced by Awasthi and Chauhan (2011). The methods are described in more detail below.

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: 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. Using AHP in solving a decision problem involves four steps.

- Step 1 (Decomposition: hierarchy design) :A complex problem is decomposed into a hierarchy with each level consisting of a few manageable elements by breaking down the decision problem into a hierarchy of interrelated decision elements via group discussion and consensus.
- Step 2 (Prioritisation: measurement of preference) : The impacts of the elements of the hierarchy are assessed and prioritised through paired comparisons done separately in reference to each of the elements of the level immediately above. Relative weights of decision elements are derived at each level.
- Step 3 (Synthesis: aggregation of relative weights) : The priorities are pulled together through the principle of hierarchic composition to provide the overall assessment (global priority) of the alternative.
- Step 4 (Sensitivity analysis) : The stability of the outcome to changes in the importance of the criteria is determined by testing the best choice against 'what-if' type of change in the priorities of the criteria.

The first step in the analytic hierarchy process is to model the problem as a *hierarchy*. In doing this, participants (or in the case of the thesis, decision makers) explore the aspects of the problem at levels from general to detailed, then express it in the multileveled way that the AHP requires. As they work to build the hierarchy, they increase their understanding of the problem, of its context, and of each other's thoughts and feelings about both. Once the hierarchy has been constructed, the participants analyze it through a series of *pairwise comparisons* that derive numerical scales of measurement for the nodes. The criteria are pairwise compared against the goal for importance. The alternatives are pairwise compared against each of the criteria for preference. The comparisons are processed mathematically, and *priorities* are derived for each node. Like probabilities, priorities are absolute numbers between zero and one, without units or dimensions. A node with priority .200 has twice the weight in reaching the goal as one with priority .100, ten times the weight of one with priority .020, and so forth. Depending on the problem at hand, 'weight' can refer to importance, or preference, or likelihood, or whatever factor is being considered by the decision makers. In the case of the thesis the 'weighting' represents the priority area of sustainability although in this scenario it is common to equalise the weights and then conduct a sensitivity analysis later to illustrate the changes in results or priorities.

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). DST allows certain limitations within the AHP method to be reduced. One criticism of the AHP method is the sheer number of pairwise comparisons to be performed before any rankings can be evaluated (Beynon et al, 2000). For example, if there were four criteria, each with three decision alternatives there would be 3 comparisons per criterion between the decision alternatives (D.A.'s) level, making 12 comparisons in all at that level. Another 6 comparisons at the criterion level, giving a total of 18 comparison judgements. The number of comparisons quickly rises as the number of alternatives and criteria rise, for example if there were a choice of 8 motorcycles considered then a total of 118 prior comparison judgements would be required. DST reduces this limitation through by allowing groups of DA to be compared, effectively minimising pairwise comparisons. A further drawback is their consistency of these comparisons. For example, if car A is preferred to B, B preferred to C also C preferred to A, this would be understandably inconsistent. This understanding of consistency is measured and discussed within the AHP method. Additionally there is no allowance for ignorance with respect to types of car and available criteria while DST supports it.

The original 'theory of evidence', created by Dempster (1968) was based around Bayesian probability inference (BPI) in that it deals with subjective beliefs and can handle qualitative as well as quantitative data values.

> *"Reduced to its mathematical essentials, Bayesian inference means starting with a global probability distribution for all relevant variables, observing the value of some of these variables, and quoting the conditional distribution of the remaining variables given the observations." (Dempster, 1968)*

DST 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.

$\Theta = \{H_1, H_2, \dots, H_N\}$ is a collectively exhaustive and mutually exclusive set of hypotheses or propositions. A basic probability assignment (bpa) is a function m: $2^{\Theta} \rightarrow [0,1]$, is known as a mass function which is conditioned via:

$$m(\Phi) = 0 \tag{5.1}$$

$$\sum_{A \subseteq \Theta} m(A) = 1 \tag{5.2}$$

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

$$2^{\Theta} = \{\Phi, \{H_1\}, \dots, \therefore, \{H_N\}, \{H_1, H_2\}, \{H_1, H_N\}, \dots, \Theta\} \tag{5.3}$$

$m(A)$ will measure the belief exactly assigned to A and represents how strongly the evidence supports A. All assigned probabilities are summed to unity and there is no belief in the empty set (Φ). The degree of ignorance is where the assigned probability is $m(\Theta)$. As mentioned earlier, the goal is to determine the level of belief within the body of evidence (ITS service performance criteria) using a plausible set of hypotheses. This can be described by each subset $A \subseteq \Theta$ so that $m(A) > 0$ which in turn is a focal element of m. All focal elements are grouped together as the body of evidence. Each bpa possesses a belief measure, Bel, and the plausibility measure, PI. Both are functions: $2^{\Theta} \rightarrow [0,1]$, and given by $\mathrm{Bel}(A) = \sum_{B \subseteq A} m(B)$ and $\mathrm{PI}(A) = \sum_{A \cap B \neq \Phi} m(B)$, where A and B are subsets of Θ, Bel (A) represents the exact support to A, i.e. the belief that hypothesis A is true; PI(A) represents the possible support to A i.e. the total amount of belief that could be potentially placed on A. [Bel(A), PI(A)] constitutes the interval of support to A and can be seen as the lower and upper bounds of the probability to which A is supported. The two functions are related to each other by $\mathrm{PI(A)} - 1 - \mathrm{Bel}(\bar{A})$ where $\bar{A}$ denotes the complement of A. The difference between the belief and the plausibility of a set A describes the ignorance of the assessment for the set A (Shafer, 1976).

m(A), Bel(A) and PI(A) are in one to one correspondence. In other words, they are all pieces of the same information. Evidence from different sources is combined using Dempsters rule of combination (Dempster, 1968). It assumes that each information source is fully independent of one another and uses an orthogonal (independent) sum to combine the multiple belief structures.

$$m = m_1 \oplus m_2 \oplus m_3 \oplus \dots \oplus m_k \tag{5.4}$$

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

$$[m_1 \oplus m_2](C) = \begin{cases} 0, C = \phi \\ \dfrac{\sum_{A \cap B = C} m_1(A)m_2(B)}{1 - \sum_{A \cap B = \phi} m_1(A)m_2(B)'} & C \neq \phi \end{cases} \tag{5.5}$$

Where A and B are both focal elements and $[m_1 \oplus m_2](C)$ is a bpa. The denominator, $1 - \sum_{A \cap B = \phi} m_1(A)m_2(B)$ denoted by K is known as the normalisation factor. $\sum_{A \cap B = \phi} m_1(A)m_2(B)$ is called the degree of conflict between the body of evidence and process of dividing by k is called normalisation. The large k is in value, the more sources that are conflicting and the lesser in their sense in their combination. If k = 0, complete compatibility between the body of evidence is attained. If 0 < k < 1, partial compatibility is achieved. The sources are completely contradictory if k = 1, therefore, the orthogonal sum does not exist. According to Shafer (1976), the rule of combination coined by Dempster allows evidence to be combined in any order. This is validated by associatively and commutatively. For example, $m_1 \oplus m_2 = m_2 \oplus m_1$ is recognised as commutative and $(m_1 \oplus m_2) \oplus m_3 = m_1 \oplus (m_2 \oplus m_3)$ is associative.

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.

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.

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. 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.

5.2.4 Scenario and Target Generation

The following sections describe the two scenarios which were developed to assess the frameworks ability to deliver context specific and valid sustainable data values. Each scenario consists of a variety of different variables. The variables within the scenarios depend upon the available or predominant technology that is in use at that time as well as the baseline targets that have been set. The following variables (discussed in detail later) will be taken into account in order to differentiate key emission targets, technological advancement and innovative services:

- Time period
- CO_2 Reduction Target
- Service Types Available
- Vehicle Power Plant

A comparison of the literature for UK and EU baseline emissions targets has led to the design of specific targets for each scenario (Tight et al, 2005; Saikku et al, 2008; Yang et al, 2009). The dates were specifically chosen as they are arguably the dominant milestones to assess the progress of climate change reduction and are in agreement with EU targets. It is important to note that for each scenario different technologies will be available. Certain technologies that provide a significant impact or change to the road network may not be currently available. For example, platooning, which assumes automated control of the vehicle may not be available until a later time period (Michaud et al, 2006; Li and Zhang, 2010). The key ITS technologies to review will be based upon the level of impact. This level is defined as the technologies representation of contribution to not only increasing road efficiency or safety but the level of carbon reduction that takes place using the service as well as the potential cost to reduce future environmental risk. In addition, the services under scrutiny are selected from a wide range of ITS technologies to ensure the model can cope with varying levels of complexity (infrastructure, components, impact) and data types.

5.3 Estimating Currently Operational ITS Service Performance

This section describes how the EnvFUSION performance framework was configured to assess ITS services that are currently in operation.

5.3.1 Selected ITS Service Type for Analysis: Active Traffic Management

Currently, the most recently operational type of ITS Service has been Active Traffic Management (ATM). 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 km 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. Table 5.1 illustrates the ATM schemes currently operational within the UK as of 2013 as well as projects that have been proposed.

Current ATM Operations	ATM Projects proposed and under construction up to 2015
M1 highway J10 to J13	M1 highway 28-31, 32-35a and 39-42
M6 highway: 4-5 and 8-10a	M4 highway: 19-20
M42 highway: 3a-7	M5 highway: 15-17
	M6 highway: 5-8
	M25 highway: 5-7 and 23-27
	M60 highway: 8-12 and 12-15
	M62 highway: 18-20 and 25-30

Table 5.1: - UK ATM schemes currently in operation and proposed

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 research illustrates the process to estimate the environmental and socio-economic impact using the case study of ATM on the M42 stretch of road.

5.3.2 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 5.2. 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 5.2).

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

Table 5.2: - Pair-wise Comparison Likert scale used within EnvFUSION

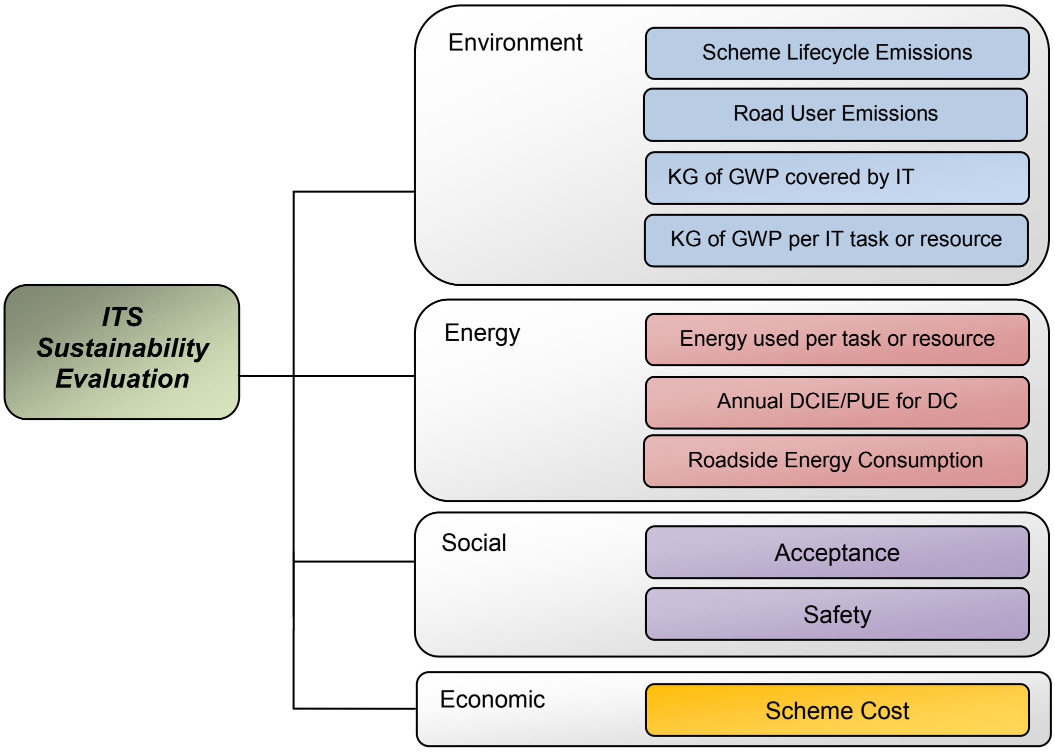

Figure 5.3: - Evaluation Criteria within the EnvFUSION framework (Source: Kolosz et al, 2013a)

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

5.3.3 LCA Emissions Modelling

The SimaPro software package was used to create and manage the attributional LCA phase of the EnvFUSION methodology in order to assess current ITS services. SimaPro was selected over other LCA software due to its professional completeness of covering the full LCA via extensive processes, materials and emissions coverage. Other advantages include an exhaustive range of impact assessment (mid-point) methods and direct integration with an integrated LCA database known as Ecoinvent (Goedkoop et al, 2010). Ecoinvent was created for a need to provide consistency across various LCA databases (Frischknecht et al, 2005; Frischknecht and Rebitzer, 2005). In the past, lifecycle inventory data did not often match up and the efforts to constantly updating vast LCA inventory processes were beyond the capabilities of a single organisation. Due to LCA receiving more credibility within the environmental sector and other industries, Ecoinvent 2000 was conceived.

> *"In parallel with the increasing trend for LCA applications, the demand for high quality, reliable, transparent and consistent LCA data increases as well. Only a few publicly available LCI databases fulfil these criteria, most of them from the 1990s and thus not up-to-date."* (Frischknecht and Rebitzer, 2005)

Several organisations were lead by the Swiss Federal Institute for Environmental Science and Technology (EMPA). The organisations within the collaboration included the Swiss federal institutes of technology (ETH), Zurich and Lausanne, Paul Scherrer Institute for Environmental Science and Technology (PSI), Swiss Federal Institute for Environmental Science and Technology (EAWAG). Together with the Swiss Agency for the Environment, Forests and Landscape (SAEFL or BUWAL), the Swiss Agency for Energy (BFE) and other Swiss Federal Offices, the Swiss Centre for Life Cycle Inventories was founded (Frischknecht et al, 2005; Frischknecht and Rebitzer, 2005). The LCA-institutes launched Ecoinvent 2000, which resulted in a harmonised, balanced and updated Swiss national and European LCI database integrated from various other databases

Within Ecoinvent, over 4000 processes are covered extensively from Swiss institutions with the emphasis on assimilating European data in order to merge ETH-ESU 96, BUWAL250 and several other Swiss databases. These processes contain European data on transport, energy, building materials, chemicals, paper and pulp, waste treatment and agricultural sectors reflecting the production and supply situation in the year 2000 based on Swiss and European demand patterns. Other advantages include consistent application of system boundaries and data, in that Ecoinvent will always include capital goods by default. Capital goods relate to the production of materials necessary to produce the product or service that is under scrutiny. As Europe is covered within the extensive database, its use for EnvFUSION is valid, particularly in terms of energy production as its coverage spans internationally. This is supported by evidence of recent studies outside Europe where for example a case study on the applicability of non-local LCI data in Brazil gave a positive correlation to the emissions results of Europe (Ossés de Eicker et al, 2010a; Ossés de Eicker et al, 2010b). The various repositories that make up the Ecoinvent database is illustrated in Figure 5.3. A description of the components in Ecoinvent is illustrated in Table 5.3 on the next page.

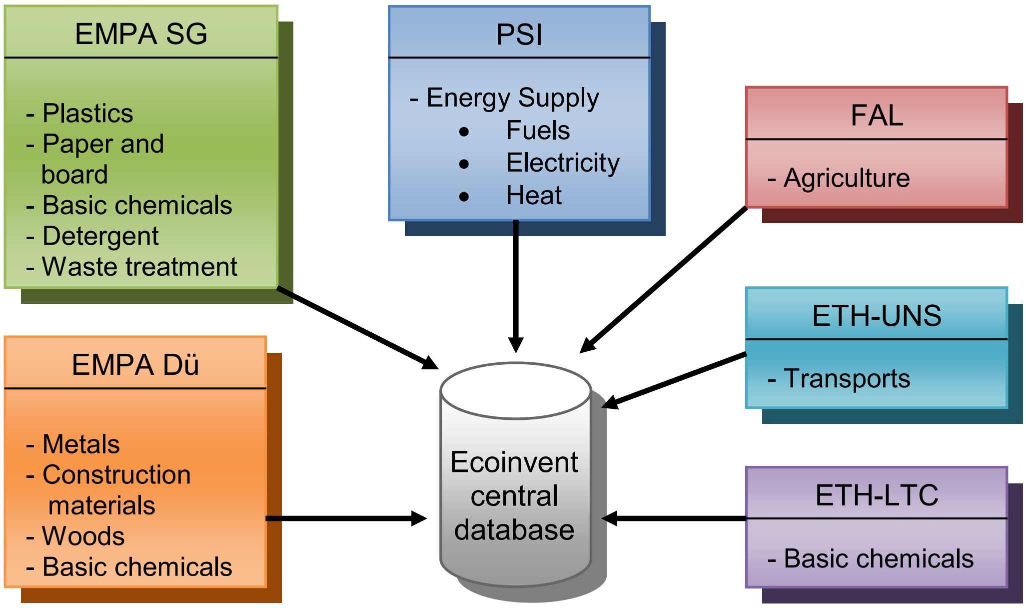

Figure 5.4: - Ecoinvent merger of datasets (Source: - Goedkoop et al, 2010)

The most notable disadvantage of the database as a standalone data source lies in its temporal delay (time frames) and questionable relevance in that some processes may be out of date or may not be covered from a UK perspective. EnvFUSION attempts to bypass this weakness via handling uncertainty in three phases. Firstly, during the assessment of unit processes within the inventory analysis of the LCA stage. Secondly, a sensitivity analysis of the LCA model after the impact assessment and finally, during and after the creation of the ITS sustainability index.

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). For the inventory analysis, Ecoinvent features its own uncertainty assessment - Ecoinvent lognormal distribution (ELD).

Components	Description
Central Database	The central database contains Life Cycle Inventory data on energy systems, transport systems, waste treatment systems, chemicals, building materials, etc., and Life Cycle Impact Assessment (LCIA) methods such as the Swiss Ecological Scarcity 1997 IMPACT 2002C (Jolliet et al, 2003), Ecoindicator 99 and the CML characterisation scheme 2001 (Pennington et al, 2004). The database is located on a computer server and accessible via the Internet.
Calculation Routines	Data are supplied by the partner institutes as non-terminated unit processes (i.e., they can and usually do contain exchanges from and into the technosphere as well as elementary flows). The computation of cumulative inventory results is performed with powerful calculation routines related to the central database. Unit process raw data as well as LCI results include (cumulative) uncertainty ranges.
Editor	The local database administrators of the participating institutes use the editor to create new data sets and to change, complete or delete existing data sets. The editor administrates the data set names (via a direct link to the central database, where the index of data set names is located), ensures the use of the actual list of names when compiling new inventories and includes a unit converter. The editor acts as the interface between the local administrator and the central database and generates files in the ecoinvent data format
Administration Tool	The administration tool supports the integration of data sets delivered by the cooperating institutes into the central database. It helps to verify the completeness of data sets, calculates inventories and (normalised and weighted, if appropriate) category indicator results and supports the administration of ecoinvent users.
Query Tool	The Query tool is the users' interface to the database and is used to download data sets from the central database. It enables the search for individual processes, for processes of a certain economic sector (e.g., transport or energy sector) or for data from a certain institute. General information (so-called meta information) on the processes (technology, age of data, geographic coverage, etc.) is accessible to everyone, whereas the quantitative LCI data is only accessible for registered Ecoinvent members (customers).
Data (exchange) format	The data exchange format lists all data fields that were available to describe a data set. It has evolved from the international SPOLD data exchange format and corresponds to the international technical specification ISO/TS 14048 [13]. Some of the data fields are mandatory, i.e. information must be provided. Among other features, the data exchange format allows for specifying upper and lower estimates (or the 95% standard deviation) as well as the probability distribution (e.g., lognormal) of inventory data.
Local databases	Commercially available LCA-software such as Emis, PEMS, Regis, SimaPro, TEAM and Umberto are used as local databases. These local databases are tailored for an implementation of Ecoinvent data v1.0 and its updates. It is recommended to use the Ecoinvent data (exchange) format for the purpose of data import.

Table 5.3: - Ecoinvent Components (Source: - Frischknecht and Rebitzer, 2005)

According to Frischknecht et al (2005), the ELD assessment takes into account the variability and uncertainty of parameters within the unit process input/output (IO) 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 method was chosen by its creators due to the emission measurements not possessing negative values which lognormal distribution does not support. The ELD method is to be used for EnvFUSION and is already integrated within the Simapro software which allows the user to run Monte

Carlo[1] analysis using uncertainty data from the ELD method (Goedkoop et al, 2010). Uncertainties are therefore handled consistently using this quantitative method. From Lognormal distribution has been interpreted for all unit processes. A unit process version contains only emissions and resource inputs from one process step, plus references to input from other unit processes. So for instance, a unit process Steelmaking, contains only *transports of hot metal and other input materials to converter, steelmaking process and casting.* This means the unit process starts at the point where molten iron comes in from another process. The environmental load connected to iron making, is described in a series of other unit processes. System processes (an LCA of specific process) does not support ELD and therefore these processes were not used for EnvFUSION due to a lack of clarity which may lead to erroneous levels of uncertainty (Goedkoop et al, 2010).

The procedure for ELD uses a combination of quantitative and qualitative assessment (Frischknecht et al, 2005). According to Goedkoop et al (2010) and Longford (2009), lognormal distributions can be characterised by a standard deviation. Standard deviation is a widely used measure of variability or diversity used in statistics and probability theory. It shows how much variation or "dispersion" there is from the average (mean, or expected value). A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data points are spread out over a large range of values.

In probability theory, a log-normal distribution is a probability distribution of a random variable whose logarithm is normally distributed. If X is a random variable with a normal distribution, then $Y = \exp(X)$ has a log-normal distribution; likewise, if Y is log-normally distributed, then $X = \log(Y)$ is normally distributed (Limpert et al, 2001). This is true regardless of the base of the logarithmic function: if $\log_a(Y)$ is normally distributed, then so is $\log_b(Y)$, for any two positive numbers a, $b \neq 1$. In a log-normal distribution X, the parameters denoted μ and σ are, respectively, the mean and standard deviation of the variable's natural logarithm (by definition, the variable's logarithm is normally distributed), which means:

$$X = e^{\mu+\sigma Z} \tag{5.6}$$

[1] Monte Carlo methods (or Monte Carlo experiments) are a class of computational algorithms that rely on repeated random sampling to compute their results. Monte Carlo methods are often used in simulating physical and mathematical systems. In the case of EnvFUSION, Monte Carlo methods are used to assess the uncertainty data emanating from the Unit Process (Manufacturing, Waste disposal etc) of an LCA.

with *Z* a standard normal variable. This relationship is true regardless of the base of the logarithmic or exponential function. If $\log_a(Y)$ is normally distributed, then so is $\log_b(Y)$, for any two positive numbers *a*, *b* ≠ 1. Likewise, if e^X is log-normally distributed, then so is a^X, where *a* is a positive number ≠ 1.

In mathematics, the geometric mean is a type of mean or average, which indicates the central tendency or typical value of a set of numbers by using the product of their values (as opposed to the arithmetic mean which uses their sum). The geometric mean is defined as the *n*th root (where n is the count of numbers) of the product of the numbers. A geometric mean is often used when comparing different items – finding a single 'figure of merit' for these items – when each item has multiple properties that have different numeric ranges. For example, the geometric mean can give a meaningful "average" to compare two companies which are each rated at 0 to 5 for their environmental sustainability, and are rated at 0 to 100 for their financial viability. The geometric mean between two numbers is:

$$f0geo = \sqrt{f1 \cdot f2} \tag{5.7}$$

The full equation for calculating geometric mean can be defined as:

$$\bar{x}_{geom} = \sqrt[n]{\prod_{i=1}^{n} x_i} = \sqrt[n]{x_1 \cdot x_2 \cdot \ldots \cdot x_n} \tag{5.8}$$

In statistics and probability theory, the standard deviation (represented by the Greek letter sigma, σ) shows how much variation or dispersion from the average exists and is calculated through:

$$\sigma = \sqrt{\frac{\sum(x - \mu)^2}{N}} \tag{5.9}$$

A low standard deviation indicates that the data points tend to be very close to the mean (also called expected value); a high standard deviation indicates that the data points are spread out over a large range of values. The standard deviation of a random variable, statistical population, data set, or probability distribution is the square root of its variance. It is algebraically simpler though in practice less robust than the average absolute deviation. A useful property of the standard deviation is that, unlike the variance, it is expressed in the same units as the data. Note, however, that for measurements with percentage as the unit, the standard deviation will have percentage points as the unit.The 95% confidence interval of cumulative LCI results is calculated with the help of Monte Carlo simulation. The 2.5% and the 97.5% values calculated with Monte Carlo simulation are shown for each individual elementary flow.

The uncertainty assessment makes use of a variety of data quality indicators featuring a pedigree matrix which is based on work already published (Weidema and Wesnæs, 1996). Six data quality criteria are used to assess each data point plus the basic uncertainty factor and are described as follows. U_1 is a reliability factor, assessing the consistency of the process as well as its ability to be trusted. U_2 represents the completeness of the data, in essence, possessing all the appropriate parts that describe and validate the process. U_3 represents the temporal correlation, are all elements that contribute to the process up to date and still relevant? U_4 represents the geographical factor, where if one process was assessed within a certain area of the world, can the data still accurately describe the same process in a different area? U_5 is the uncertainty factor representing the technological correlation, taking into account the technology used and accurately describing its process. U_6 represents the sample size, how many times has the process been extracted from similar cases relevant to the data that is under scrutiny. Finally U_b represents the basic uncertainty factor in the form of a quantitative data value that is based upon expert judgement (Frischknecht et al, 2005; Frischknecht and Rebitzer, 2005; Goedkoop et al, 2010). For example, experts realise that CO_2 emissions can be quite precise and can be easily checked against the fuel input while other substances may prove harder to establish an accurate reading such as poly aromatic hydrocarbons and fine particles (PM^{10} and $PM^{2.5}$) etc, hence their overall factor is high. Table 5.4 illustrates the uncertainty factor scoring criteria used by the ELD method. 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 (5.10)

$$SD_{G95}^2 = \sigma_g^2 = exp^{\sqrt{[\ln[(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \quad (5.10)$$

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 chosen 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 this framework.

Score	1	2	3	4	5
Reliability (U1)	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
Completeness (U2)	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
Temporal Correlation (U3)	Less than 3 years of difference to our reference year (2000)	Less than 6 years of difference to our reference year (2000)	Less than 10 years of difference to our reference year (2000)	Less than 15 years of difference to our reference year (2000)	Age of data unknown or more than 15 years of difference to our reference year (2000)
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
Geographical Correlation (U4)	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown OR distinctly different area (north America instead of middle east, OECD Europe instead of Russia)
	1.00	**1.01**	**1.02**		**1.10**
Further technological Correlation (U5)	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00		**1.20**	**1.50**	**2.00**
Sample Size (U6)	>100, continuous measurement, balance of purchased products	>20	> 10, aggregated figure in environmental report	>=3	Unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

Table 5.4: - Uncertainty Factor Scoring Criteria (Source: Goedkoop et al, 2010)

The Global Warming Potential model was extracted from the Intergovernmental Panel Committee on Climate Change's 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).

5.3.4 ICT operational efficiency criteria

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 5.5.

Parameters/Criteria	Display Format
Energy used for task or resource	KWh
CO2 per task or resource	KG CO2
Kg of CO2 offset	KG CO2
Kg of CO2 covered by renewable energy certificates	KG CO2
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 5.5: - ICT Infrastructure Criteria (Source: Kolosz et al, 2013a)

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, an independent division of the 451 group based in New York (Stansberry and Kudritzki, 2012).

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \tag{5.11}$$

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.

5.3.5 Information Fusion and Indicator Estimation

The data (basic probability assignments and mass functions) are required for each of the criteria (Figure 5.2), 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 5.6 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 5.6: - Performance Sustainability Scale (Source: Kolosz et al, 2013a)

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:

$$DTT_{(i)} = ASB_{(i)} - FST_{(i)} \tag{5.12}$$

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.

$$PR_{(i)} = \frac{FST_{(i)}}{ASB_{(i)}} \tag{5.13}$$

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:

$$r_i = \sum_{k=1}^{p} r\,(G_k)\ \times bpa\,(G_k)\ \times DTT_i \qquad (5.14)$$

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 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 global performance ranking.

5.3.6 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 $C_1, C_2, \ldots, C_N$ are denoted by r_1, r_2, r_3,... r_N. An ITS sustainability index value is then given by combining:

$$ITSI = r_1 \times w_1 + r_2 \times w_2 + \ldots + r_n \times w_n \qquad (5.15)$$

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 summed performance ranking of the index, which sorts the criteria from highest performing area of ITS to areas which perhaps require more focus. The ranking of the index is between 0 and 1. This is determined via the values of the BPA, DTT and AHP values which are also calculated between 0 and 1 which then provide the ITSI values using the equation (5.14).

5.3.7 Missing Data and Managing Uncertainty

In terms of the case study, after the first phase of data collection is complete (extracting the EPI'S from the literature, public domain and external reports) the second phase of the case study commences which involves the collection of production and operational variables taken from the M42 Managed Motorway suppliers. This is to reduce the uncertainty of suppliers producing materials with varying manufacturing processes which could produce a serious impact on the emissions results when assessing the Managed motorways scheme at this location. For EnvFUSION, this can be defined as the first order of uncertainty, relating to the variability in the supply chain of each supplier as well as the differences in the type and quantity of materials. Furthermore, the versions of infrastructure attached to the M42 pilot are designated as Version 1 with other ATM schemes being given a classification of Version 2. This is in order to distinguish the pilot scheme from all other schemes here on in.

To reduce uncertainty to a minimum, case study data was extracted only from the suppliers involved with the M42 pilot. For reasons of data anonymity, all emissions data and energy values were averaged, based upon the sample size and in case there was more than one supplier providing similar ITS infrastructure. The data was then screened for anomalies such as incompleteness, inconsistency and redundancy. This process is vital to the working of the EnvFUSION model in order to maintain an accurate record of emissions throughout the model so that the endpoint[2] method could be interpreted from a reliable source. By the end of the screening of the literature, if supplier data was missing or had not been recovered, assumptions were made based upon available data that was collected from suppliers who were not involved in the M42 pilot as well as the scrutiny of existing LCA results.

According to Frischknecht et al (2005) there is a slight variation with the probabilistic mean values (cumulative results from the Monte Carlo simulation) and deterministic mean values (cumulative results derived from the mean values of the unit process raw data without the use of uncertainty factors). These values are therefore available to scrutinise within the Ecoinvent database.

> *"This has the advantage that the mean values of the LCI results are reproducible. Furthermore, the reliability of the mean values of the unit process raw data is judged to be much higher as compared to the roughly estimated geometric standard deviation." (Frischknecht et al, 2005)*

With regards to impact assessment, no minimum or maximum values are shown within the results. Current impact assessment methods do not support uncertainty information (Pennington et al, 2004). However, Simapro features its own uncertainty engine which will be used in tandem with the EnvFUSION methodology. Once the impact assessment was completed, a full analysis of uncertainties within the model was extrapolated. The uncertainties included representativeness (data from process coming from different sources or regions to the one that is under scrutiny) which the impact may be difficult to estimate, Allocation (system expansion) of the various products from a production line, future events (what new

[2] An endpoint or end point is a mark of termination or completion. In terms of the EnvFUSION model, the endpoint method is the categorisation and normalisation of criteria within the proposed sustainability index.

technologies were available and did the lifecycle need to be adapted to accommodate this). Finally, the choice of the functional unit which indicates the focus product or object needed to be assessed. In this case, the assessment of GHG emissions emanating from the ITS managed motorways infrastructure on junction 3a to 7 of the M42. This is explained further in this chapter. According to Goedkoop et al (2010), a Monte Carlo analysis, is not usually enough to take into account factors that represent the entirety of the model, therefore a sensitivity analysis was the most appropriate option. Taking into account issues of completeness (is all data correct and accounted for?) unavoidable data gaps such as materials with unknown quantities of emissions, unidentified production and waste processes etc could occur which would have drastically affected the results of the impact assessment. The following factors were taken into account for EnvFUSION to prevent and reduce the impact of data gaps on the model.

The system boundaries which indicate the scope of the Lifecycle Assessment and which processes to include needed to be completely relevant to the product under focus. The first step to achieving this within the model was to perform a quick screening of the product using data already obtained with some assumptions (erroneous data and estimations for large data gaps) and to set the system boundary at its widest possible state. In other words, including all processes and LCA stages related to the material extraction, manufacture, operation and disposal of the Managed Motorways scheme, setting the emissions cut-off to zero (all processes shown).

Once this was performed, the next step was to identify which processes would carry the greatest burden of emissions. It is these processes that would determine the majority of the results and the emissions cut-off for example, needed to be set to include these processes wide enough to encompass all aspects relevant to the functional unit and the scope of emissions pertaining to ITS, but at the same time, not too wide to lose the context of the goals and objectives of the study. For EnvFUSION, further data was gathered from interviews and also through questionnaires in an attempt to clean and rectify these events. Some data according to Goedkoop et al (2010) is gathered from sum parameters such as BOD (biochemical oxygen demand) and PAH (Polyaromatic hydrocarbons). Problems may be encountered within the impact assessment if the substances have not been declared sufficiently (incorrect measurement units etc) to a point where the mid-point method used to categorise the data does not recognise the substance at all. Finally, if there is a mismatch, between the inventory analysis and impact assessment for example, materials that do not have a characterisation factor (grouping of emissions into a larger group, example climate change etc) the finding is ignored within the LCA. Once again, the functional unit and system boundary should be carefully specified and focused in order to avoid vital data being overlooked.

> *"Especially because of the last two types of uncertainties, it is difficult to apply a uniform system to deal with uncertainties in LCA. The best solution is to combine Monte Carlo analysis for data uncertainties with sensitivity analysis for model uncertainties." (Goedkoop et al, 2010)*

The literature argues that performing a sensitivity analysis during and after the LCA is essential to understand the major impact of the assumptions involved but also to determine whether the design of the model is accurate enough to be useful (Arvanitoyannis, 2008; Finnveden et al, 2009; Goedkoop et al, 2010; Ahlroth et al, 2011). Changing the assumptions and recalculating the model grants a different perspective on how the system holds together and will allow the analyst to determine its dynamics. A handful of assumptions will prove crucial to how the model operates and should be determined in the goal and scope as well as the data collection phase.

Within the Simapro software, parameters can be utilised as switches, therefore allowing the boundaries and allocation definitions to be altered for alternative scenarios, although these scenarios may only focus on the change of processes within the LCA model. Available information during the LCA phase cannot determine the significance or level of uncertainty within the estimation of environmental performance due to the limited primary (supplier) data and there is only one background data source (Ecoinvent) with information providing a mono value. This is the key difference between the ELD uncertainty phase in the LCA and the creation of the sustainability index within the EnvFUSION methodology. This is due to the latter uncertainty phase being handled via a form of Bayesian probability inference (BPI) using the Dempster-Shafer (D-S) method and can not only handle missing data via extracting relevant transport and ICT data sets from multiple information sources, but can also reinforce harmonisation and consistency.

5.4 Forecasting Future ITS Service Performance

This section discusses the second unit of analysis which is the forecasting of future ITS services up to 2050.

5.4.1 Selected ITS service types for analysis

ATM as described earlier respresents the current state-of-the art in dynamic traffic management and is currently being implemented internationally (Mirshahi et al, 2007; Fehon and Klim, 2010; WSDoT, 2012), However, there are some issues with ATM. The technology relies on fixed roadside infrastructure that incurs high levels of embedded emissions during its lifecycle. This is due to the manufacturing processes of the parts which usually involves customization of components, also requiring substantial levels of energy during the process. As part of the second unit of analysis within the case study other technologies were explored which represented the most promising impact that ITS sytems could have on the M42. Each technology represents a very different configuration and therefore different implementation challenges.

Intelligent Speed Adaptation or ISA is a technology designed to restrict the speed limit of a vehicle depending upon the type of road and geographical location (Agusdinata et al, 2007; Spyropoulou and Karlaftis, 2008). It is one of the technologies under the collective banner of Driver Assistance Systems. Three types of ISA have been proposed under two main configurations which are Passive or Active. Advisory is passive and informs the driver if the speed limit is exceeded, Voluntary is active and restricts the speed limit at the discretion of the driver, whilst Mandatory makes it compulsory for the system to remain active via judicial law (Lai and Carsten, 2012).

ISA offers a number of potential benefits including reducing the number of serious and fatal accidents as well as reducing emissions on highways. In more recent studies, the ability of the vehicle to 'know' the speed limit via GPS technologies as opposed to fixed infrastructure will also reduce the need to procure road-side equipment which in turn reduces embedded emissions. AHS provides services and support infrastructure required for vehicles to drive autonomously while the driver is effectivley disconneted from operations (Michaud et al, 2006). At the core of AHS is Cooperative Vehicle Infrastructure Systems in the form of vehicular ad-hoc networks. More recently, integration with cloud computing has enabled vehicles to form platoons, creating digital links which reduce the distance of vehicles at high speed (Sok-Ian and Tonguz, 2011; Hussain et al, 2012). Naturally, this creates excellent flow efficiency allowing traffic throughput to vastly increase. Vehicular Ad-hoc networks allow the continuous exchange of information such as speed, acceleration, braking and obstacles.

5.4.2 Criteria Selection and Weight Allocation

It was decided that in order to capture the full focus of environmental and socio-economic performance four forecasting models would be created, each belonging to a certain performance group representing environment and socio-economic perpsectives. The criteria used in order to estimate the performance of current ITS services was also applied to forecasting, although the data values would be dynamic and based upon marginal variations in performance as time moves forward.The forecasting models relate to the performance criteria as illustrated in Table 5.7**.**

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

Table 5.7: - Forecasting models applied to Performance Criteria (Source: Kolosz et al, 2013b)

The values of the criteria are compared with a Distance-to-target (DTT) method which allows for pre-defined future targets to be compared with the marginal values of the criteria during each timestep within the simulation (Weiss et al, 2007). These targets can be determined by local, regional and international government bodies and institutions. Whilst DTT was originally an LCA method to evaluate and prioritize the different environmental impact categories, in this paper it has been expanded to incorporate a range of sustainability aspects and modified to give an aggregated score, whilst AHP handles prioritization. The reduction targets can be achieved by improvements in technology. Using a modified version of the Distance-to-target method used by Lin (Lin et al, 2005), the weighting and percentile of the initial performance state is calculated via

$$DTT_{(initial)} = ASB_{(initial)} - FST_{(initial)} \quad (5.16)$$

or if the target should be of a higher value, (1) is inverted. With $DTT_{(tbase)}$ being the distance-to-target value dependent on the context of the criteria in focus, $ASB_{(tbase)}$ the apparent level of sustainability burden and $FST_{(tbase)}$ the future sustainability target. We refer to sustainability in this context as a subjective value which takes into account all facets of evidence in the form of a sustainability index (representing the group of criteria). The following equations are used to calculate the performance of criterion with negative (5.17) or positive (5.18) distance to target values.

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{ASB_{(tyear)}} X\ 100 \quad (5.17)$$

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{FST_{(tyear)}} X\ 100 \quad (5.18)$$

5.4.3 Research Approach to Data Management

Understanding the structure and flow of data within ITS is a prerequisite to developing the correct standards in order to control key aspects of a VANET and other data centres. In addition, how this data is secured is vital to ensure the safety and integrity of the system (Chim et al, 2010; Ma et al, 2010). As part of the potential framework to be developed determining the level of data and information efficiency from factors of safety, integrity and control were to be assessed. Transmission and data types are critically analysed and selected depending on the specific scenario. Security would be assessed via a set of parameters based upon currently existing technology and protocols. A key element of the research approach is determining how the data types can be coordinated in the most optimal framework. The performance measures would determine if the data model is suitable via a quantitative grading system. The characteristics of the grading system could include:

- The ability to block and remove data noise, ambiguity and fuzziness
- Ability to reinforce data integrity via suitable security protocols
- The ability to maintain a real-time data stream
- The accuracy and strength of the transmission source and its receiver
- The ability of the system to adapt in case of data misuse/terminal errors

Data management also forms distinct relationships between the levels of adaptability within the system. The relationship is between the connection modes and the ability of the transport network to adapt in case of system or data failure.

The quantitative values attached to these elements would therefore share the same grade or value when the weights have been further developed from the research.

5.4.4 Research Approach to Standardisation

The goal of the analytical review is to understand standardisation from a highway perspective and is geared towards the relation of communication within the actors of vehicular networks and the traffic control centre. In relation to the research project, standardisation will be assessed through the use of subjective measures. They are subjective because standardisation cannot be measured via a quantitative approach. However, in order to focus the desired research outcome, the author has defined four segments of ITS standardisation based on the literature which will need to be calibrated to a low carbon unifying policy. The four segments of standardisation, regardless of region, manufacturer or standard body must be successfully unified across all standards in order to ensure compatibility, competence and successful operation of an ITS network. Communication Devices consist of the various forms of communication devices which will maintain a vehicular network. The specifications of these devices vary and all have individual characteristics which express their strengths and weaknesses. For example, current GPS technology features a very high degree of compatibility between vehicle receivers and other systems, however the accuracy is low (around 5-10 metres). Figure 5.4 illustrates these four segments.

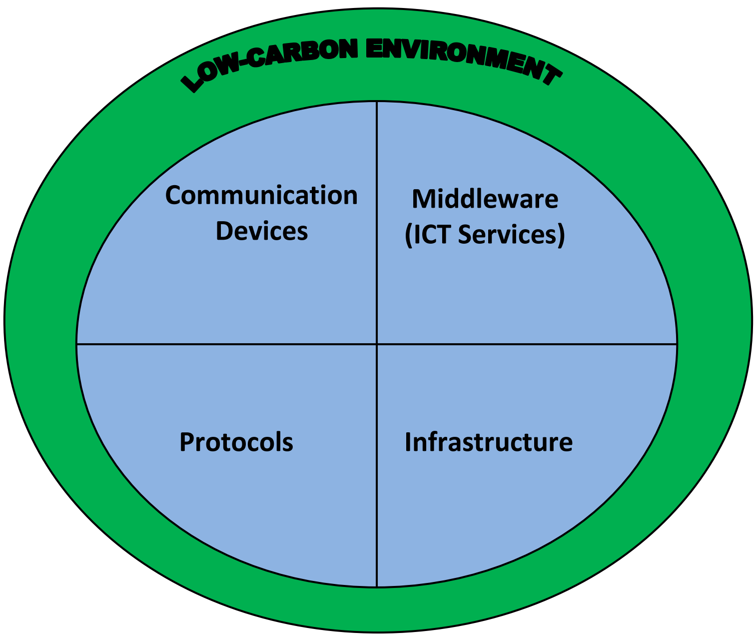

Figure 5.4: - Standardisation segments in the context of a low-carbon environment

Middleware includes the ICT layer of an integrated Intelligent transport control module. Dullaert et al (2009) proposes middleware in the form of a real-time decision support system which utilises agent-based software development techniques which utilising a set of protocols will be able to ‘handshake’ with other systems and provide improved safety and economic value. Protocols can be related to the language which the system will utilise in order to authenticate other systems, process information and set security levels. Protocols may also help to maintain stability within VANET networks. Taleb et al (2007) proposed a stable routing protocol which consists of an algorithm to maintain a vehicles connection to the network in case of signal loss which can be caused by the vehicles movement. Spanos and Murray (2004) refer to this phenomena as *Geometric Connectivity Robustness*: the ability of a network to remain stable while the source is constantly travelling even though the OD has changed.

Infrastructure, in terms of intelligent transport systems and in relation to this research may include three different groups: a road-side infrastructure (sensor networks, toll-systems etc), dynamic infrastructure (vehicles) and control infrastructure (traffic control centres, satellites etc). In addition, ICT infrastructure while noted in the literature is also valid but should not be confused with the middleware segment of the ITS-ICT layer. It should be noted that infrastructure has a direct relationship with the environment and is a lever in the proposed change to a low carbon environment. The physical network should therefore be energy efficient and the appropriate indicators in place to determine this (Lo et al, 2010).

5.4.5 Research Approach to Adaptability

The research approach to the KPI encompasses a variety of pointers towards maintaining a successful level of adaptability. A series of objective measures designed to give a suitable indicator of adaptableness could be developed in order to verify the following criteria: -

- Resource Sharing
- Systems Compatibility between regions (i.e. border crossings etc)
- Geometric Robustness
- Socio-Technical Support Services
- User Trust
- Response Times

These attributes should be given quantitative values depending on specific scenarios in order to produce a grading system. It is anticipated that three bands will be developed to determine the level of adaptability followed by recommendations for each. The first band will be the poorest and will suggest deep rooted changes will be required for the network to remain adaptable while the third band will give the highest rating (very little changes are required). Each attribute will also possess a series of flags (guidelines) to assist in the evaluation of the network.

5.5 Chapter Summary

This chapter has discussed the model assessment and integration strategy for the methods that were defined in Chapter 4 as being suitable for use within the study. The next chapter illustrates the implementation of a study on Active Traffic Management based upon the methods proposed and the data collection strategy.

"ATM was first introduced by the Highways Agency in September 2006 on the M42 between Junctions 3A and 7. An important feature of the M42-ATM scheme was establishing the concept of Hard Shoulder Running (HSR) – used for the first time in the UK – together with variable mandatory speed limits during periods of congestion" (Ogawa et al, 2010).

Chapter 6 - Evaluation of current inter-urban ITS systems: Active Traffic Management

This chapter introduces the case study (assessing current sustainable performance) based upon Active Traffic Management, current 'fixed' infrastructure aimed at reducing congestion on the road network as an alternative to carbon intensive projects such as road widening. The data collection procedure with regard to environmental performance indicators is presented and the steps to the development of the study are illustrated. The results of the study are then discussed along with a sensitivity analysis of the associated weights.

6.1 M42 ATM Case Study: description and primary data collection

This section illustrates an overview of the case study based on the estimation of current Inter-Urban ITS systems. Active Traffic Management was selected as the ITS service to be assessed. The primary data collection process based upon the model integration strategy and system boundary in Chapter 5 is presented.

6.1.1 Overview

In order to illustrate the data collection process, it is necessary to define the scope of the infrastructure within the particular case study of the M42 ATM. The ATM features gantries spaced 500 m apart and feature several components as illustrated by Figure 6.1 (other schemes in the UK position these at 800 m).

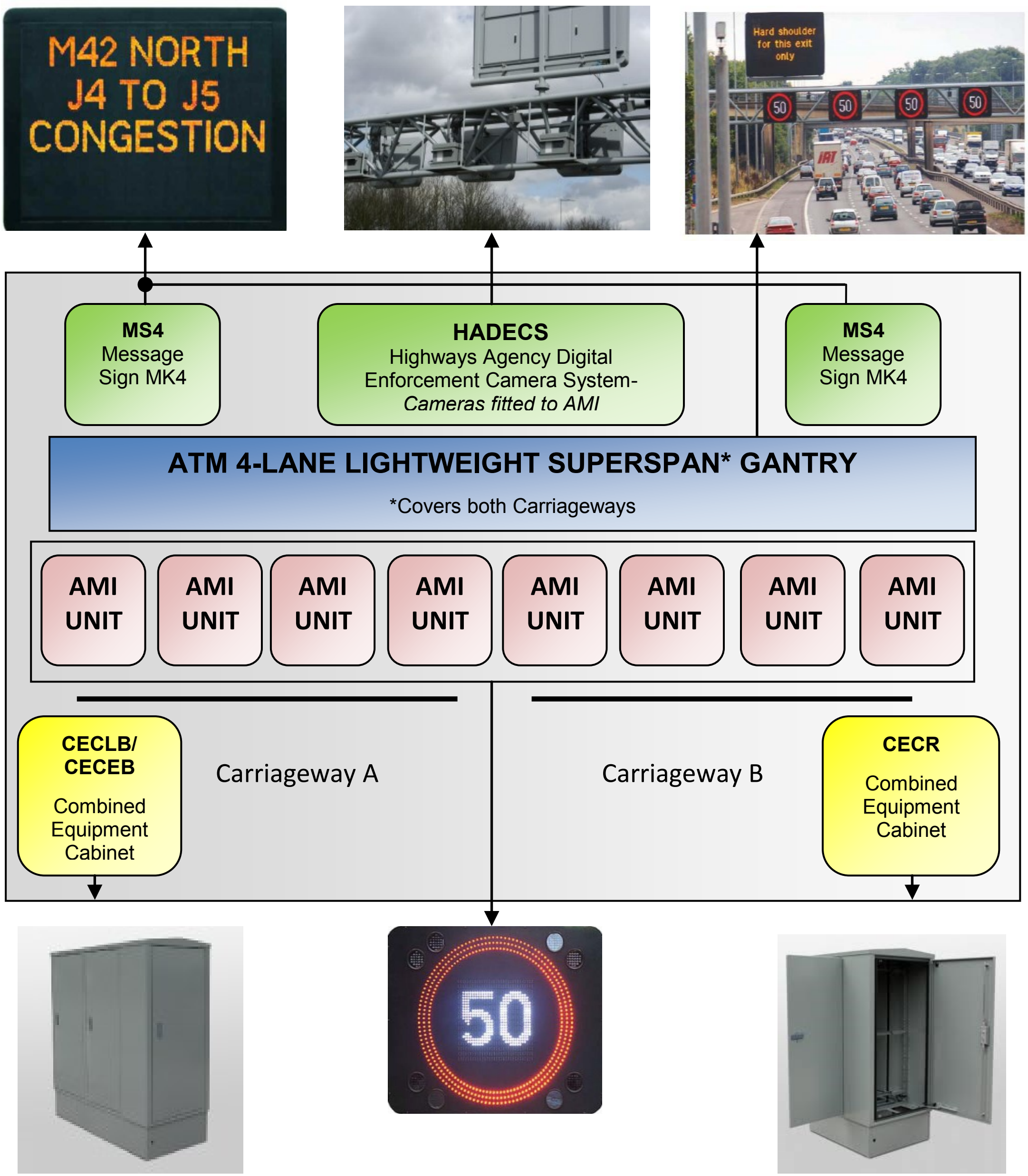

Figure 6.1: - Typical UK ATM Gantry Inventory (Source: Kolosz et al, 2013a)

The infrastructure comprises a lightweight superspan gantry (covering 2*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. 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 (Figure 6.2). 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).

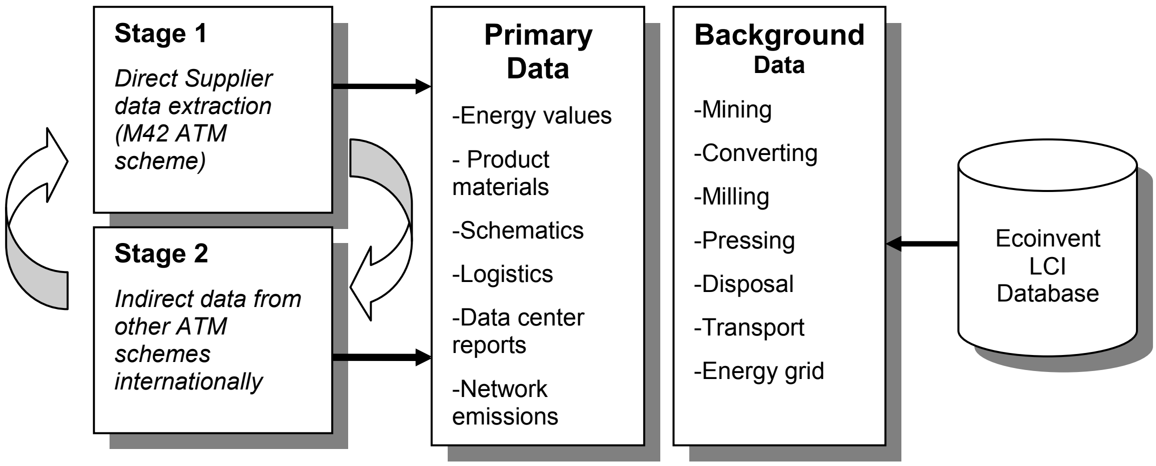

Figure 6.2: - Data collection Process (Source: Kolosz et al, 2013a)

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.

6.1.2 Primary Data: Vehicle Emissions

In order to calculate the vehicle emissions, the following figures were taken from the assessment of the M42 ATM scheme. Mott Macdonald, a consultancy selected for measuring the before and after impact of the M42 'pilot' scheme listed several primary and secondary performance indicators (Mott Macdonald, 2009). The complete list of indicators is shown below in Table 6.1.

Primary Indicators	Secondary Indicators
Throughput and Peak throughput	Speed differential between lanes
Average Journey Times	Duration of Speed less than x mph
Variability in journey times	Frequency of speed less than x mph
Speed limit	Flow/speed plots
Number and severity of Accidents	HGV percentage
Noise	Lane utilisation
Emissions and Air Quality	Headway distribution
User consultation	Vehicle speed distribution
	Vehicle hour delay

Table 6.1: - ATM M42 'pilot' pre and post-test Performance Indicators (Source: Mott Macdonald, 2009)

The indicators highlighted in green represent areas that are applicable to the study. The assessment of emissions and air quality was produced in November 2007. The baseline was described in the environmental analysis report conducted in 2003 for the assessment of emissions once the ATM pilot implementation was completed (McCrae and Barlow, 2005) and the summery of the operational results were presented to the ITS World Congress in New York, 2008. Recently, an assessment was completed which indicated it would be feasible for ATM to operate at 60MPH on the hard shoulder as opposed to the original 50 MPH speed limit. The revised speed limit is now currently in effect and the change in speed possesses no bearing on the environmental impact of ATM as supported by the literature (Ogawa et al, 2010).

A recent study of trends in NO_X, CO_2 emissions and ambient measurements which was undertaken in order to understand why these GHG's have not decreased in the UK has led to several critical findings (Carslaw et al, 2011). For ambient concentrations, two characteristics are made clear; a decrease in concentration from 1996 to 2002-2004 followed by a more stable period from 2002/2004-2009.

These observations are influenced sectorally from all areas of the UK including inter-urban and urbanised roadside sites.

> *"Over the period 2004–2009 the annual percentage reduction in NOx concentrations has been in the range 1–2%, although trends at motorway sites have been greater ≈ 3.5%. Corresponding trends in NO2 have been decreases in the range 0.5 to 1% per year, although rural sites have shown a greater decrease ≈1.4% per year." (Carslaw et al, 2011)*

This indicates that ambient trends in the concentrations of NO_x and NO_2 have not decreased by as much as suggested by current UK emission factors. Emissions data from 72,000 individual vehicles were analysed from a vehicle emission remote sensing detector (RSD) technique. According to the literature (Bishop et al, 1989; Ashbaugh et al, 1992; Sadler et al, 1996), RSD techniques were originally developed in the USA to measure the emissions of poorly maintained vehicles with a high emissions factor. Remote sensing measurements were made using the RSD-4600 supplied by Environmental Systems Products (ESP, Arizona, US) as a dedicated across-road vehicle emissions monitoring system. Individual vehicle plumes are measured from passing vehicles by shining a UV/infrared beam of light across the plume. The measurements include the concentration ratio of NO, CO, HC and a measure of 'smoke' to the concentration of CO_2. A record is defined as a beam block (by a vehicle) followed by a half second of data collection. If the data collection is interrupted by another beam block, i.e. a following vehicle with a headway less than 0.5 seconds, the measurement attempt is aborted. The capture of a valid record does depend on several factors. These include the size of the observed CO_2 emission plume is sufficient to allow emission ratios to be calculated, and the vehicle speed is in the range 5 to 60 km h^{-1}, and a clear digital image of the vehicle's number plate is captured

The technique is based on field studies led by the University of Leeds and Enviro Technology plc. The location where these studies were conducted means that they best represent urban-type driving conditions and not higher speed driving that would be expected on motorways for example. Although it does give an insight into the depth of the problem and the level of correction and realignment required for the environmental performance results to remain critically accurate. In addition, the data has been scrutinised with current UK emission factors and alternative emission factor estimates from the 'Swiss/German Handbook on Emission Factors'

(HBEFA) and COPERT 4[1] (COmputer Programme to Calculate Emissions from Road Transport). The RSD provides a clear indication of where there are discrepancies between currently-used emission factors and in-use factors. According to the authors, these are among the most important findings of the work (Carslaw et al, 2011). The NO_x (Nitrogen-oxide) emission factors for diesel cars and LGVs given in COPERT 4 and HBEFA are higher compared with those in the UK emission factors (UKEF) for Euro 3 (2000-2005 vehicles onwards). The RSD suggest much greater NO_x emission factors for Euro 1 (1992-1996) and 2 (1996-2000) petrol cars than are currently used in the National Atmospheric Emissions Inventory (NAEI). Estimate agreement is more precise for Euro 4 (2005-2009) petrol cars. For diesel cars and LGVs, the RSD indicate higher emission factors than used in the NAEI across all Euro classes, but this difference gets progressively larger for the later Euro classes as the reduction in emission factors implied by the UKEF does not seem to have occurred. For rigid HGVs, there is reasonable consistency between the RSD and UKEF.

For a new Euro 5 (2009-2014) petrol car, emissions are estimated at 96% less NOx than a pre-catalyst vehicle. The RSD data illustrates that NOx emissions from Euro 1/2 (and to some extent Euro 3) are higher than either the UK emission factor estimates or HBEFA. These results imply that catalyst degradation and the emissions control system used on petrol vehicles as a whole, is consequently more vital than previously understood and that older catalyst equipped cars are important emitters of NO_x. For diesel cars/vans the RSD suggests that there has been little change in total NO_x emissions over the past 20 years or so. NO_x emissions from HGVs were static until Euro IV, where the emissions decreased by about one third. The RSD data does however show that bus emissions of NO_x have been static, or even increasing over the past 10–15 years. However, the bus emissions are affected by specific fleet characteristics. These findings indicate that the EIA that was originally carried out at pre and post evaluation of the ATM scheme features deficiencies in that it underestimates the level of NO_x emissions. Considering emissions of NOx as a function of *Vehicle Specific Power* (VSP) shows that under higher engine load conditions (i.e urban driving using lower gears and stop start manoeuvres) there is a clear increasing emission of NO_x for Euro 3–5 diesel cars

[1] Copert 4 is an MS Windows software tool for the estimation of emissions from road transport. The emissions estimated include all major pollutants (CO, NOx, VOC, PM, NH3, SO2, heavy metals) as well as greenhouse gases (CO2, N2O, CH4). The programme also provides speciation for NO/NO2, elemental carbon and organic matter of PM and non-methane VOCs, including PAHs and POPs.

that is not apparent for older generation vehicles. Euro 3–5 diesel cars can emit up to twice the amount of NO_x under higher engine load conditions compared with older generation vehicles, possibly the result of the increased use of turbo-charging in modern diesel cars. Another assumption as discussed earlier is that the current diesel petrol market distribution split is inaccurate. *Absolute* emission estimates which are sampled at site using emission equipment for passenger cars are higher than suggested by currently used emission factors. This findings will therefore have an influence on the relative emissions calculated by vehicle type i.e. these vehicles will be relatively more important emitters than previously thought. It may also mean that total road transport NO_x emissions are higher than previously thought, although detailed inventory calculations will be required to confirm this.

In order to re-calculate the original baseline EIA assessment for the ATM M42 pilot, it is important to analyse the proposed revision of the emissions inventory statement which was carried out in the second part of the recent study by Carslaw et al (2011). Although the authors suggest more work will be required to fully revise and integrate the new NO_X calculations due to the high complexity of the inventory in the UK, the transfer of these first steps into EnvFUSION will remain crucial in order to maintain high accuracy and low uncertainty in determining the true benefit ATM has upon the environment and traffic throughput. The base case conditions such as the unadjusted most recent UK/London inventory estimates illustrate a downward trend in NO_x and is dominated by reductions in emissions from petrol vehicles. Over the period 2002–2009 the NAEI calculations for UK urban emissions show a reduction in NO_x from diesel vehicles of about 24%. Taking account of the RSD emissions data reverses this downward trend for diesel vehicles to an increase in NO_x emissions of 18% over the same period because of the increase in diesel vehicles (cars and LGVs) together with RSD that suggests that NO_x emissions have not decreased. This is an important change to projected emissions over that period. Nevertheless, this increase in diesel NO_x emissions is still more than off-set by decreases in petrol vehicle NO_x emissions.

> *"Because the RSD only provides a snapshot in time (effectively what was on the road around 2009), we have no observational emissions data relating to what these vehicles emitted when they were new or for the intervening years." (Carslaw et al, 2011)*

Before an improved emission inventory calculation methodology can be developed with confidence, further information is necessary. This includes: more sophisticated information on the extent of SCR use in the UK HGV fleet, better information on the changing emissions performance of petrol vehicles over time and more accurate information on the vehicle stock age profile and distance travelled. In terms of this case study, estimated environmental performance offset was adapted through percentage ratios based upon the results of the lifecycle assessment and was forecasted up until the year 2020 using estimated vehicle market figures to compensate for the inaccurate petrol/diesel split.

6.1.3 Primary data: Standard Gantry Equipment

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 6.2 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 6.2: - Highways Agency's initial inter-urban ATM material weighting calculations (Source: Kolosz et al, 2013a)

The data in Table 6.2 was considered the initial calculation of inter-urban ATM schemes and forms the second phase of the data collection as discussed below. It should be noted that there are several discrepancies as the Carbon Accounting Framework estimates the weight of a lightweight super span gantry at approximately 18 tonnes, whilst the LCA material analysis indicated a substantially heavier weight at 39 tonnes. Also the combined equipment cabinets feature different weightings to the table described above. The author concludes that only the gantry's 'Main Truss' had been taken into account in the HA's estimates (Figure 6.3). The cabinet weightings in the table are presumed to derive from obsolete equipment.

6.1.4 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.

Having profiled, drilled and sawn the necessary items for gantry construction, they are fabricated into a Gantry by Metal Active Gas welding. The structure is rotated with overhead cranage to allow the welding to be undertaken in a flat position. Having tested the structure both visually, dimensionally and with magnetic particle inspection and ultrasonic testing it is released to the Finishing department for treatment. During and after painting the structure is inspected for compliance with the specification requirements. The gantry is then transported to site and erected in accordance with an approved method statement. Each gantry is treated as an individual structure and materials are delivered to the shop floor on this basis. Common components such as AMI and supporting frames are fabricated in bulk and assigned to each gantry depending on how many of each component is required. According to the supplier, this method of fabrication ensures that the gantry trestles will always match the gantry end frames to ensure that during the short erection period all components fit together without the costly need to alter any item on site. Indeed this is paramount concern to ensure road closure is kept to a minimum and road programs are maintained.

Appendix A illustrates the quantity, grading and calculations performed of each type of steel used in the production of the gantries based upon the specifications given by the contractors who produced the gantries. 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). The calculations were therefore performed thoroughly in order to estimate the total weight of the gantry. Figure 6.3 over the next page illustrates a typical ATM gantry with the weighting distribution of each section visible.

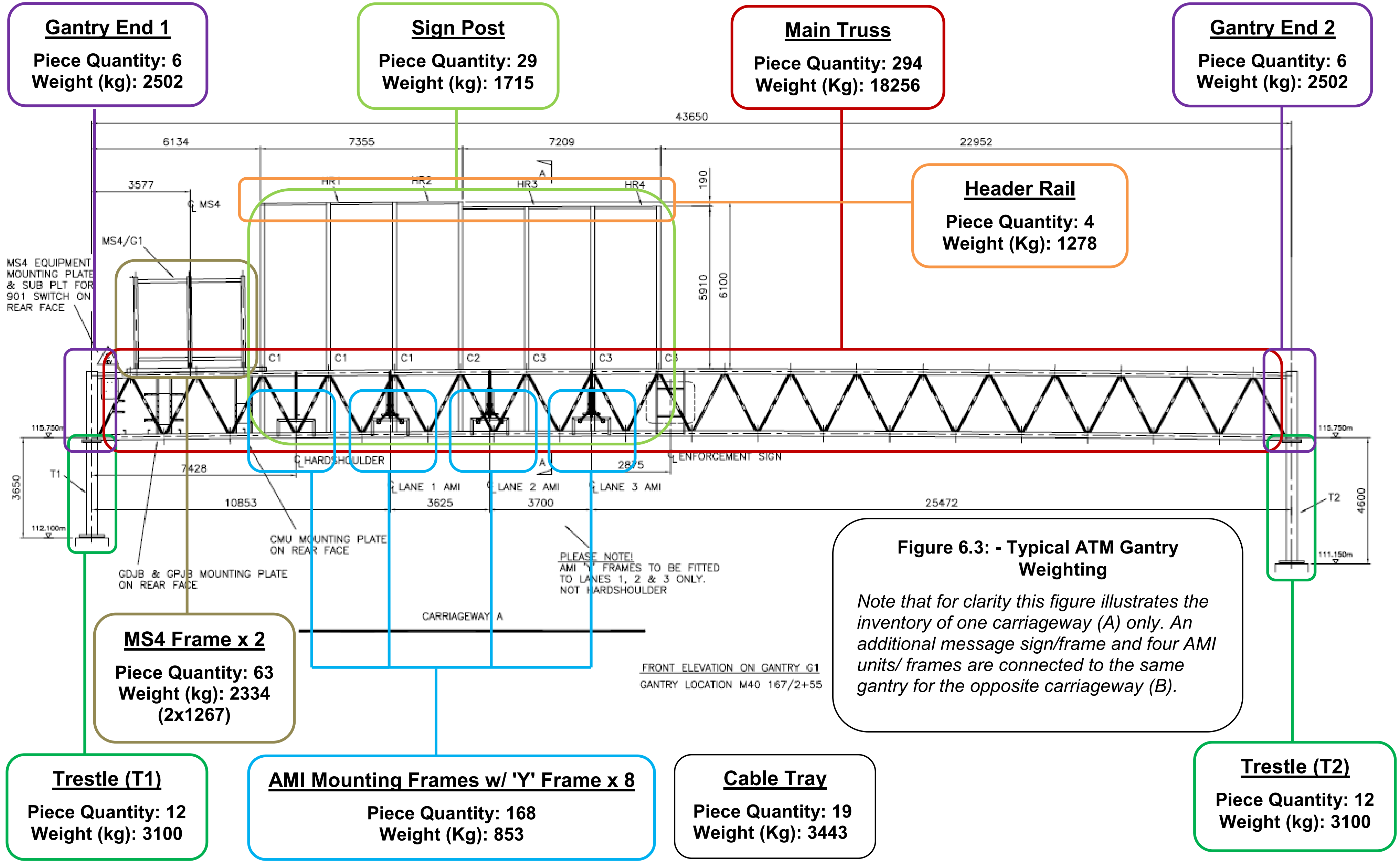

Figure 6.3: - Typical ATM Gantry Weighting

Note that for clarity this figure illustrates the inventory of one carriageway (A) only. An additional message sign/frame and four AMI units/ frames are connected to the same gantry for the opposite carriageway (B).

Because of the discrepancies of the total gantry weight between the road network operator and the material weighting calculations applied in this study, the gantry data in Figure 6.3 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.

6.1.5 Primary data: Message Sign (MS4)

The design and reliability of electrical/electronic components has progressed since the introduction of the Motorway Signal Mark 2 (MS2) in the early 1990s and the MS3 in the late ‘90s (Highways Agency, 2008). Advances have been made in Light Emitting Diode (LED) technology that enables a wider viewing angle and a higher resolution display with two colours. These developments have been incorporated into a new generation of motorway signal, known as the Motorway Signal Mark 4 (MS4). The MS4 increases the intelligibility of information by the use of internationally recognised warning symbols and is a 4m wide x 3m dual colour matrix sign, capable of displaying both text and pictograms. For the provision of the MS4, two suppliers were contacted (anonymous for this report) to supply MS4 environmental data for Junctions 3a to 7 of the M42. Table 6.3 illustrates the MS4 supplier specification comparison in order to determine uncertainty between manufacturers.

Specification	Supplier 1	Supplier 2
Enclosure	Fully Welded Aluminium	Fully Welded Aluminium
Dimensions	4440mm Width x 3160mm Height x 165mm Deep	4440mm Width x 3160mm Height x 165mm Deep
Weight	725 Kg	624 Kg
Conformity	Highways Agency Specification MCE 2214, European Standard EN 12966 and TR2516B	Highways Agency Specification MCE 2214, European Standard EN 12966 and TR2516B
Communications Protocol	UK highways Agency NMCS2	UK Highways Agency NMCS2
Operating Voltage	180 - 260V 50/60Hz	180 - 260V 50/60Hz
Maximum Power	2700 Watt maximum operating load	2700 Watt maximum operating load

Table 6.3: - MS4 Supplier Specification Comparison

The standard MS4 sign is capable of displaying text from 160mm to 400mm. The sign is also capable of displaying pictograms up to 2000mm. This type of sign is used on roads up to and including 70mph.

Each matrix consists of over 24,500 pixels, each 20mm pixel pitch made up from one red and one yellow LED. Detailed images can be displayed, giving rich and accurate driver information over the previous MS3 incarnation, hence the system possesses the capability of displaying virtually any text message or pictogram. The LED panels are overlaid with a matt black aluminium panel, perforated by slits at the LED locations. The LEDs are positioned at the end of matt black conduits, behind the front panel, to minimise reflections from the sun and to define the viewing angle of the display. s designed to present a high contrast highly visible display of text and pictogram messages in amber and/or red colours respectively. In addition, amber “virtual lanterns” may be embedded anywhere in the display, thus replicating the existing lantern warning signalling already familiar to the motorist in other signs. The MS4 can also display such warnings simultaneously with appropriate text messages, thus providing the motorist with more information about driving conditions than was previously possible. The main communication and control system for the sign is housed in a 19" rack mounted roadside cabinet, fitted with integral display. According to the suppliers, this provides user-friendly diagnostics; fault finding and system upgrade capability, without the need for high level access to the sign. Formatting the sign setting data received from a 2-wire NMCS2 (RS485) communications link allows the messages and pictograms to be set.

The MS4 based upon the description of a variety of different suppliers is made from an outer casing which is produced using fully welded aluminium while the windows are made from polycarbonate with internal stiffening provided by extruded aluminium box sections. All welding is carried out by automated welding machines and the electronic components are stuffed onto the PCB's by robot before being run through a solder bath. Finished PCB's and components are fixed into the signs by hand along with wiring looms etc. The weight of the whole unit differs between suppliers; however in general, it is produced using the following components (Table 6.4).

6.1.6 Primary Data: Advanced Motorway Indicator (AMI)

Following a similar production process to the MS4, Advanced Motorway Indicators (AMIs) are primarily designed for installations crossing motorway gantries and slip road entry sites, for the display of variable speed restriction and lane control aspects. Table 6.4 illustrates the components and weighting of the AMI. Designed to meet the requirements of Highways Agency Specification MCE0197 and EU Specification EN 12966, the AMI offers Positive Optical Feedback enabling high

MS4 Component Description	Quantity (Approx.)	AMI Component Description	Quantity (Approx.)
Polycarbonate	40 kg	Polycarbonate	15 kg
Printed Circuit Boards (complete with components)	60 kg	Printed Circuit Boards (complete with components)	24 kg
Miscellaneous Electrical devices (heaters, fans, power supplies etc)	60 kg	Miscellaneous Electrical devices (heaters, fans, power supplies etc)	18 kg
Paint	40 kg	Paint	6 kg
Aluminium	400 kg	Aluminium	9 kg
Stainless Steel fixings (nuts and bolts etc)	24 kg	Stainless Steel fixings (nuts and bolts etc)	24 kg
Stainless steel mounting brackets	6 kg	Stainless steel mounting brackets	6 kg
Total Weight	**624 kg**	**Total Weight**	**102 kg**

Table 6.4: - MS4/AMI Components and Weighting

quality legal enforcement. The AMI much like the MS4 features an aluminium enclosure. The display comprises a central dual colour LED matrix and surrounding red ring, both of which may be equipped with full optical and electrical monitoring for use with associated speed enforcement equipment. Four dual colour LED lanterns are fitted as standard to all AMI. The sign has a status indicator window at the side giving a quick glance view of power, data (send and receive) and fault indication enabling maintainers basic fault diagnosis from the ground. The design of the enclosure is coupled with a quick release mounting bracket design, the time required for installation and removal of an AMI is kept to the absolute minimum. Communication and control electronics for up to 16 AMIs are housed within a 19" rack mounted roadside controller fitted with integral display. This is known as an RCV2 (Roadside Controller version 2). By keeping all of the 'intelligence' within the RCV2, installation and maintenance engineers may carry out the majority of system commissioning, upgrades and fault finding processes without the need for high level access. Additionally the RCV2 allows the sign to be interrogated over an internet protocol. Table 6.5 illustrates the AMI supplier specification comparison in order to determine uncertainty between manufacturers.

6.1.7 Primary Data: Combined Equipment Cabinets (CEC)

Combined equipment Cabinets are used to store a variety of different hardware including power supplies, standard transponders, MIDAS outstations and transponders, and telephone responders along with other miscellaneous equipment associated with CCTV cameras (Highways Agency, 2009a).

Specification	Supplier 1	Supplier 2
Enclosure	Fully Welded Aluminium	Fully Welded Aluminium
Dimensions	1480mm high x 1840mm wide x 300mm deep	1840mm high x 1485mm wide x 210mm deep
Weight	100Kg	96Kg
Conformity	Highways Agency Specification MCE 107, European Standard EN 12966 and TR2516B	Highways Agency Specification MCE 107, European Standards EN 12966 and TR2516B
Communications Protocol	UK highways Agency NMCS2	UK highways Agency NMCS2
Operating Voltage	180 - 260V 50/60Hz	180 - 260V 50/60Hz
Maximum Power	200 Watt maximum operating load	260 watt maximum operating load

Table 6.5: - AMI Supplier Specification Comparison

Access to these cabinets is likely to be required by several organisations including the maintenance contractor, the enforcement equipment maintainer and the fire service. Access is controlled by a Permit to Access system Major benefits in combining this equipment into a single cabinet includes ease of access, minimal downtime on the motorway and clustering which reduces the number of cabinets required. Maintenance resources need to be provided to take account of the expected level of maintenance activities over the life-time of the scheme. It is important to ensure that sufficient space is made available in the cabinet for anticipated future technology needs. In particular, the NRTS contractor should be consulted as well as other stakeholders. It is also important to note that there are special requirements for HADECS 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. 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 CEC-R 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 CEC-R. Within enforcement areas the CEC-LB 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.

ATM also integrates Emergency refuge areas (ERA) which offer an area of relief from traffic every 800m when the temporary shoulder running is not available at certain points within the road network (Highways Agency, 2009a; Simpson et al, 2010). The ERA's location has increased from the typical 500m which are standard throughout the network and is used for traffic experiencing vehicle problems or other emergencies. Additional CCTV equipment is therefore required to monitor breakdowns and traffic flow. CCTV features an addition of several components. The CCTV equipment is located on the CECLB if applicable and the centralised equipment cabinet designation changes to CECEB. Unfortunately due to legislation, the location and number of enforcement areas is lacking, therefore uncertainty exists due to the emissions being potentially higher in these locations due to the extra equipment and energy requirements. Therefore an uncertainty analysis has been included to show the potential increase based upon known assumptions of equipment location.

6.1.8 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, 2009a) 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 6.6 illustrates these conversions applied to each ITS component within the scheme. Additional energy results are available in Appendix A. Based upon the apparent (VA) peak values from the implementation guidance, the correct value for the M42 ATM pilot is approx. 21 kW per km which increases to 29 kW per km in enforcement areas with the addition of the Highways Agency Digital Enforcement Camera System and fixed CCTV.

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	2200	0.9	1.980
	Maintenance Equipment	690	0.9	0.621
	Roadside Equipment	480	0.9	0.432
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
NRTS Load (Rectifiers -Backup)	N/A	2500	0.9	2.250
Message Sign MK4	N/A	1215	0.9	1.093
Advanced Motorway Indicator	N/A	185	0.9	0.166
	Total	**9150**		**8.235**

Table 6.6: - Energy conversion of ITS components (Source: Kolosz et al, 2013a)

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 h operation per annum (roughly 11 h 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 h 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 Telecommunication 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[1] (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).

Figure 6.4 illustrates the energy consumption per km for the M42 (500 m spacing) and other ATM schemes (approx. 800 m spacing) which were introduced at a later date.

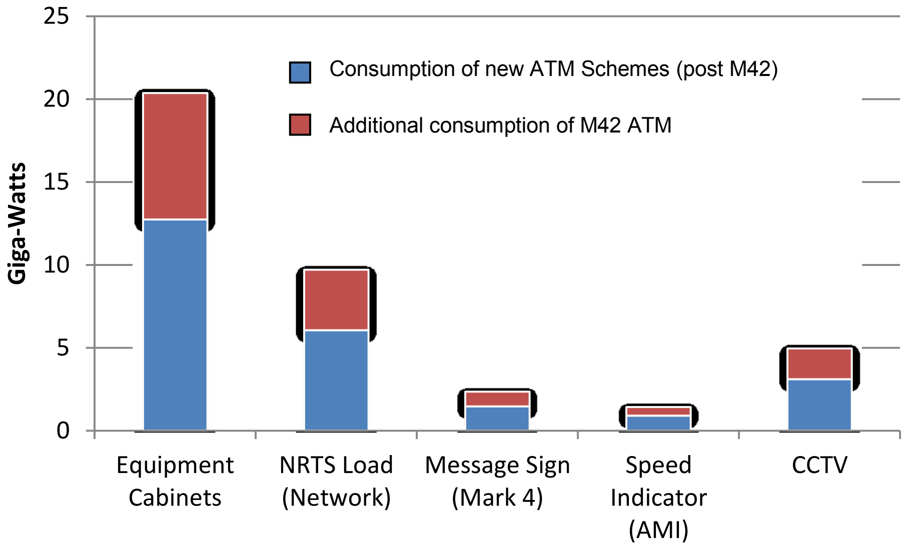

Figure 6.4: - Energy Consumption for M42 Pilot scheme and Other ATM

From Figure 6.4, the energy consumption of ATM with 4-lane temporary shoulder running is approximately twice that of the previous ATM scheme and then escalates considerably during an annual and lifespan calculation. According to the implementation guidance, an additional reserve capacity of 10% is provided for any minor upgrades or priority requirements in the future. From Figure 6.5, the energy requirements of a standard gantry is illustrated. Enforcement locations require

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[1] The author refers 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. In addition, 2020 was set so that results from the performance assessment can determine if key targets in that period have been met.

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.

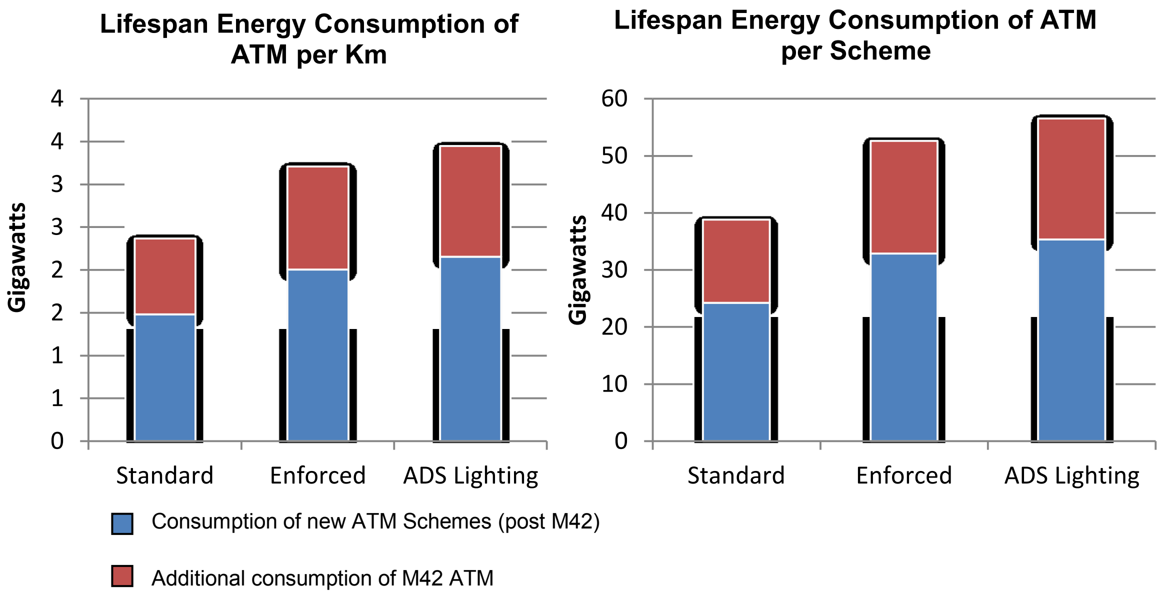


Figure 6.5: - Energy Consumption of ATM per KM and per Scheme (Source: Kolosz et al, 2013a))

The consumption of new ATM differs from the M42 pilot due to the spacing of each gantry which is 800 m while the M42 features gantries spaced at 500 m. Following collection of all the necessary primary data for the scheme infrastructure, the EnvFUSION method could then be applied as described in Section 6.2 below

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

6.2.1 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 km, 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 (Chapter 5, Figure 5.2) 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.

6.2.2 LCA Emissions Overview

The functional unit describes the rationale of the LCA exercise. Within the EnvFUSION model, the functional unit is used to channel the data gathered from the EPI's into a workable context which will rule how the data is used. This includes the expected duration of the usage of the ATM infrastructure. Although the usage of temporary shoulder running varies depending on a number of factors such as the location, weather and road works and if there is a current incident in progress, various assumptions are to be made but have been simplified to ensure the data can be managed more adequately. The functional unit is defined below:

'The assessment of Greenhouse gas emissions at Junctions 3a to 7 of the M42 strategic corridor within the production, use and disposal of key ATM infrastructure and road users during a period of 15 years (from 2005) up to 2020. 2020 has been picked as the lifetime boundary due to the transport CO_2 reduction target requirement of 34% as indicated by the UK government'

Firstly, according to the Highways Agency Implementation guidance (2009a) it is assumed that the operation of the ATM infrastructure will be carried out via three different power modes or operating regimes. The operating regimes are Normal State, 3-Lane Variable Mandatory Speed Limits (3L-VMSL) and 4-Lane Variable Mandatory Speed Limits (4L-VMSL with controlled use of the Hard Shoulder). In addition, a further two modes can be identified: Incident management (for when there is a collision or natural disaster event etc) and Emergency Refuge Area management (for vehicles that breakdown, drivers to recover etc). Due to simplification purposes it is assumed that operating under these circumstances does not cause fluctuation with the energy requirements but may cause minor fluctuations in vehicle emissions, therefore the model will not attempt to simulate these conditions. When temporary shoulder running is operating at normal state, it will be at its lowest power configuration (standby with energy consumption at 0), message signs and indicators will be blank and there will be no intervention.

The hard shoulder is open only to emergencies and the three standard running lanes (LBS2, 3 and 4) are operating within the confines of the national speed limit. 3L-VMSL according to the highways agency is effectively delivering a controlled motorways environment where the primary goal is to reduce congestion, harmonise the flow of traffic, improve driver information, reduce secondary time accidents and improve journey time reliability. 3L-VMSL is operated automatically via the use of MIDAS (Motorway Incident Detection and Automatic Signalling). Sensors under the road and supporting software utilises algorithms to prevent the onset of queues as well as managing congestion.

> *"MIDAS automatically sets 60mph, 50mph and 40mph speed limits in LBS2, 3 and 4 to delay the onset of flow breakdown and so improve the throughput of vehicles and improve journey time reliability. Inductive loops monitor traffic flows and speeds and the Controlled Motorways algorithm set speed limits accordingly. As a minimum this is likely to occur during the morning and evening peaks each week day." (Highways Agency, 2009a)*

When MIDAS operates within queue protection mode, speed limits are automatically set via its High Occupancy Algorithm (HIOCC) in addition to a message on the MS4 which can state either 50/60 MPH and "queue Ahead" or 40 MPH and "queue warning". 4L-VMSL features full temporary shoulder running operation with the hard shoulder being used as a running lane (LBS1). It reverts back when the extra capacity is no longer required and it is apparently not feasible to move from normal operating regimes to 4L-VMSL. This is because the traffic must adapt slowly to the change of modes rather than cause confusion with a sudden change of motorway protocol (Highways Agency, 2009a). To simulate heavy congestion (PK - peak network capacity), the FU also assumes that temporary shoulder running is activated twice a day, during the morning and evening for 4 h each. In the morning it is activated between 7:00 and 11:00 and in the evening between 15:00 and 19:00. The time is quite generous but some locations such as the M42 feature extended periods of peak capacity. The FU is therefore based upon the M42 'pilot' peak network periods (McCrae and Barlow, 2005). Over a lifespan of one year the following calculation for assessing the peak period takes place.

$$\mathrm{PK} = 365 \text{ x } 8 \qquad (6.1)$$

The life time of the infrastructures components and sub-components depends upon the Mean time Between Failure (MTBF) of the various components of the infrastructure. For simplification purposes, when a component encounters a fault, the component (including all sub-components) is replaced with an identical counterpart. This is usually the most likely outcome and the maintenance replacement value will give levels of CO_2 equivalency and other materials involved in the lifecycle assessment a positive multiplier of 2 specific to the new components. Assumptions of the future must also be assessed. As time passes by, new versions of components will become available that work at a lower power and feature improvements in the production and maintenance as well as an improved MTBF. While all of these factors are significant, it is important to recall the scope of the case study which is in the short-term, analysing between 2005 - 2020. Within this period, expert advice will be sought out from the stakeholders involved.

The operational management phase focuses on the energy and embedded carbon analysis. This process shares a consequential relationship with the operation of the vehicle that is currently navigating through the road network. As there are variety of different vehicles, their efficiency gain from the ITS service will vary. Simplification methods will be placed upon the type of vehicles that will be analysed and is discussed further in the report. This relationship is determined through the introduction of an ITS carbon and carbon offset metric which is introduced after the LCA phase of the EnvFUSION model is complete. The maintenance and repair process is based upon the repair and maintenance of the ATM infrastructure. The last step includes the process of upgrading the existing infrastructure as new technology becomes available. Various assumptions are therefore made regarding the future but are carried out in the second study (Chapter 7).

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 6.6 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.

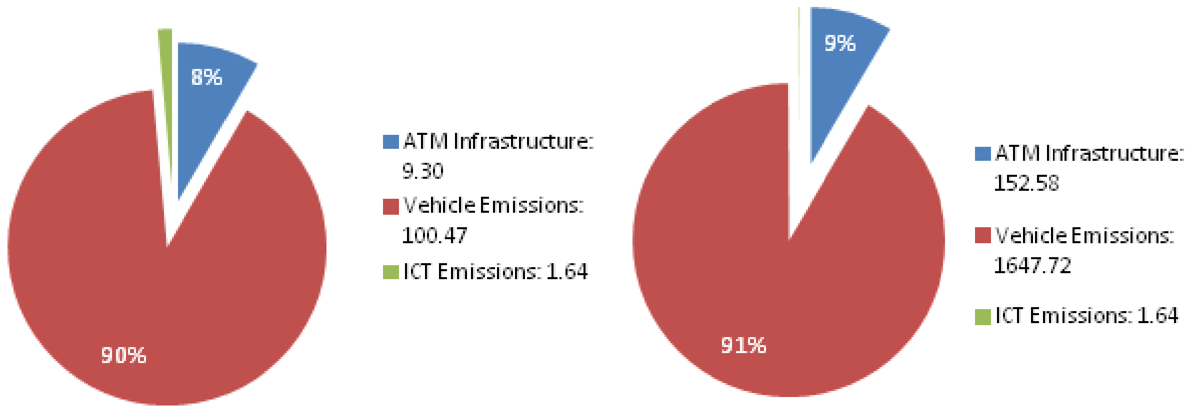


Figure 6.6: - Overall GWP of ATM in MtCO2eqv (Left: Per KM, Right: Per Scheme) (Source: Kolosz et al, 2013a)

6.2.3 ATM Infrastructure Emissions

Estimated emissions results for individual ITS components are outlined below. The value is in tonnes of CO_2 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.

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 m while the results in brackets indicate the difference in emissions of more recent ATM schemes (post M42) at 800 m. Full emissions results including the listing of Ecoinvent unit processes are available in Appendix B.

GHG Substance in kg CO_2eqv (800m 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	1346 (841)	12,570 (7856)	9916 (6197)	8082 (5051)	45,454 (28,409)	15,668 (9793)
Ethane, hexafluoro-, HFC-116	22 (14)	10,172 (6357)	296 (185)	152 (95)	27,746 (17,341)	4116 (2573)
Sulphur hexafluoride	286 (179)	5274 (3296)	6296 (3935)	1950 (1219)	17,874 (11,171)	116 (73)
Methane, tetrafluoro-, CFC-14	92 (57)	16,482 (10,301)	180 (112)	108 (68)	10,134 (6334)	1758 (1099)
Carbon monoxide, fossil	3672 (2295)	3562 (2226)	756 (472)	468 (293)	8162 (5101)	230 (144)
Methane, biogenic	314 (196)	1022 (639)	110 (69)	78 (49)	4112 (2570)	676 (423)
Methane, chlorodifluoro-, HCFC-22	8 (5)	640 (400)	44 (27)	28 (18)	2564 (1603)	92 (58)
Carbon dioxide, land transformation	8 (5)	332 (207)	82 (51)	64 (40)	1306 (816)	24 (15)
Remaining Substances	3476 (2172)	40 (25)	646 (404)	98 (61)	72 (45)	2584 (1615)
TOTAL OF ALL COMPARTMENTS	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 6.7: - Kg CO_2 Equivalency of GHG substances for ATM infrastructure per km up to 2020 (Source: Kolosz et al, 2013a)

6.2.4 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 (6.2):

$$Traffic_{CP} = AADF_{CP} \times Length_{link} \times 365 \qquad (6.2)$$

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 6.8 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	3978	17	184	576
Nitrous Oxide (NOx (Equivalent of $N0_2$)	18	2291	124	611	4548
Hydrocarbons (Equivalent of $CH_{1.85}$)	21	261	4	33	116
Ultimate Carbon Dioxide (CO_2)	2874	534,191	17,359	24,728	1,005,101
All Compartments	3165	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	3616	5151	209,396
All Compartments	660	112,649	3647	5323	210,487

Table 6.8: - Tonnes CO_2eqv for M42 junction 3a-7 vehicle emissions up to 2020 (Source: Kolosz et al, 2013a)

Figure 6.7 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 76 kilo-tonnes of CO_2 equivalency will be offset by 2020 due to the direct usage of the ATM scheme.

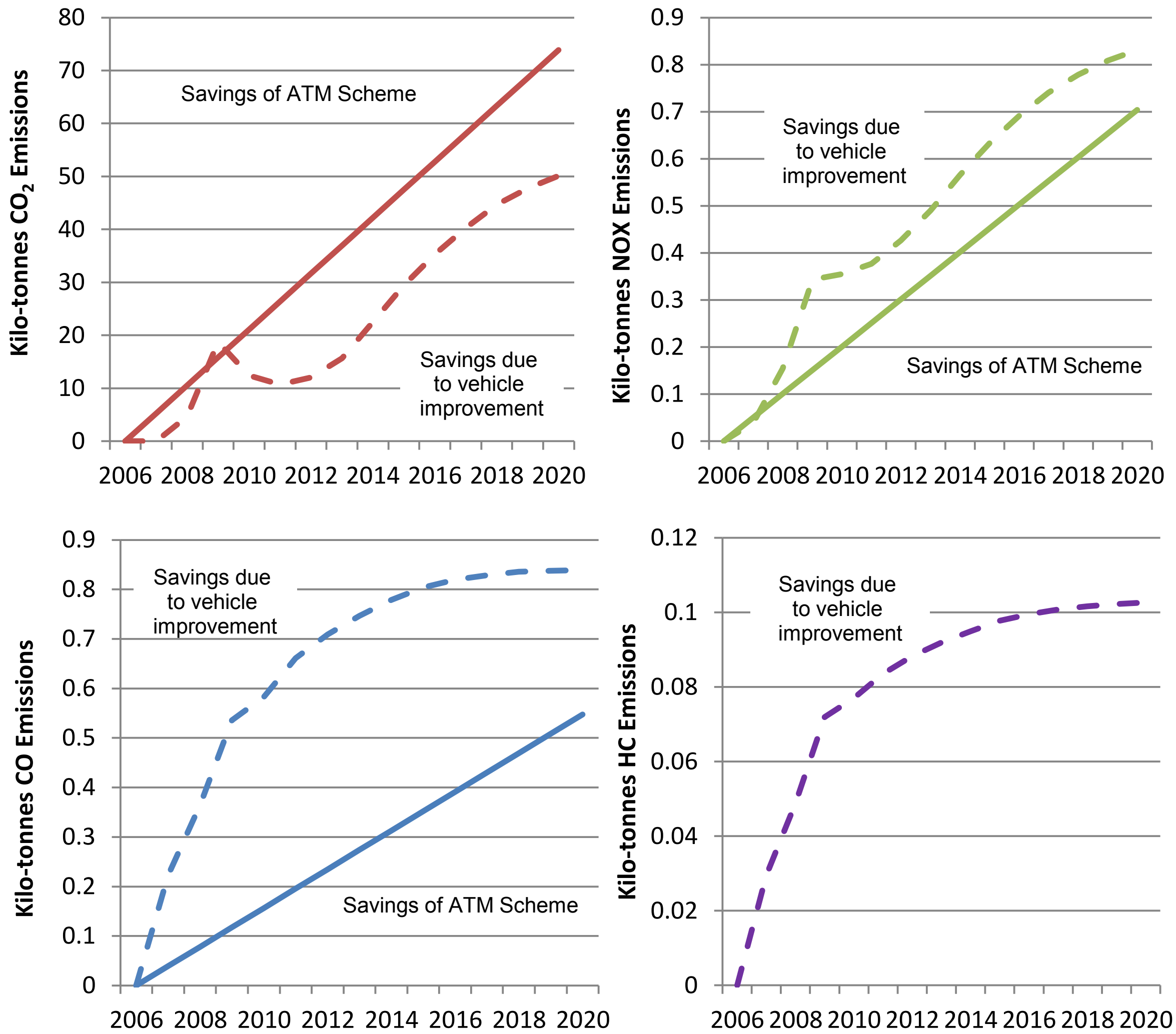


Figure 6.7: - Vehicle Emission Cumulative Savings of GWP (Source: Kolosz et al, 2013a)

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 6.8).

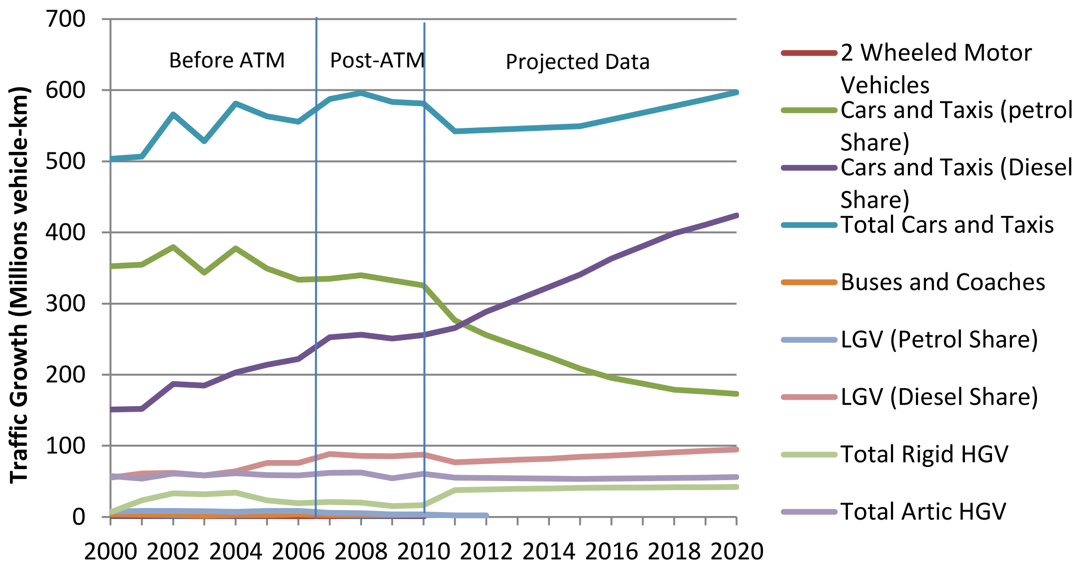


Figure 6.8: - M42 J3A-7 Annual Traffic Growth (Source: Kolosz et al, 2013a)

6.2.5 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 6.9 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 6.9: - ICT Environmental Status of Regional Traffic Control Center (Source: Kolosz et al, 2013a)

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.

6.2.6 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 6.8 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 6.8 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 6.9 illustrates global warming potential uncertainty compared with the uncertainty of other environmental factors in the LCA inventory.

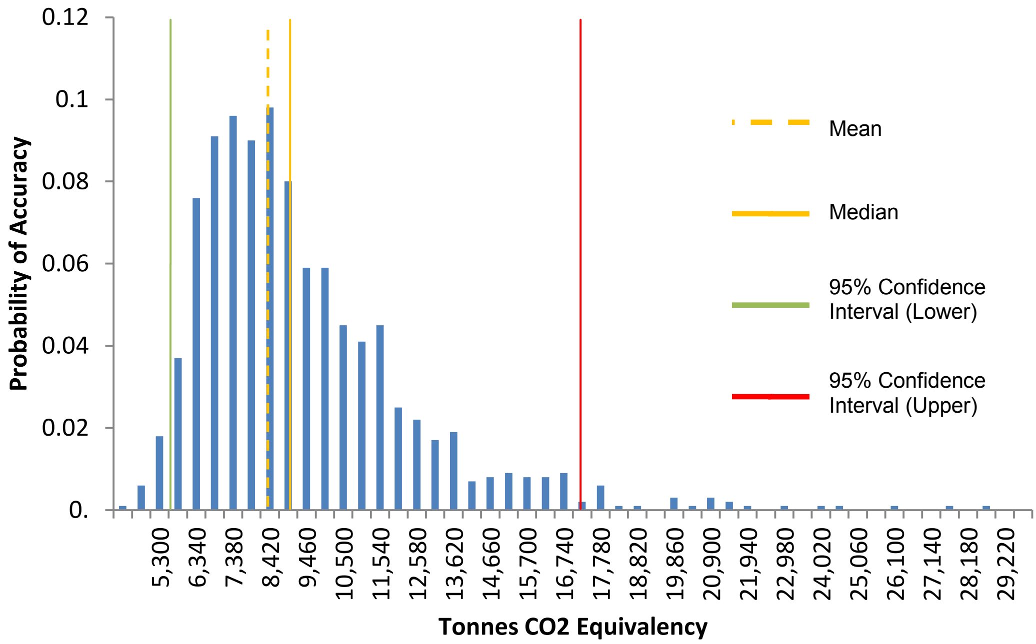


Figure 6.9: - Lifecycle emissions uncertainty: Global Warming Potential (GWP 100) (Source: Kolosz et al, 2013a)

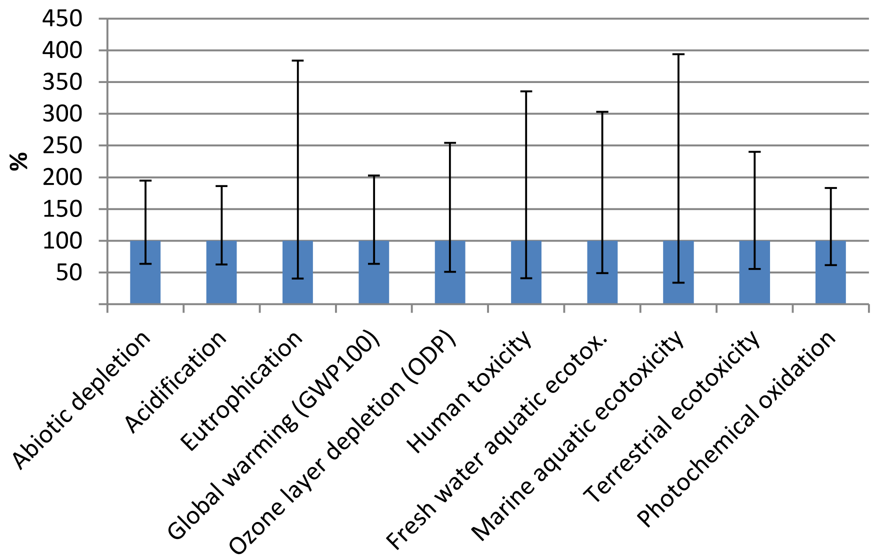


Figure 6.10: - Comparison of Lifecycle characterisation uncertainty (Source: Kolosz et al, 2013a)

From Figure 6.10, 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.

6.3 Data Fusion and Indicator Estimation

Data collection[2] 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). The DST rule set is available in Appendix C.

Figure 6.10 over the next page 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

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

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 $VH = 0$.

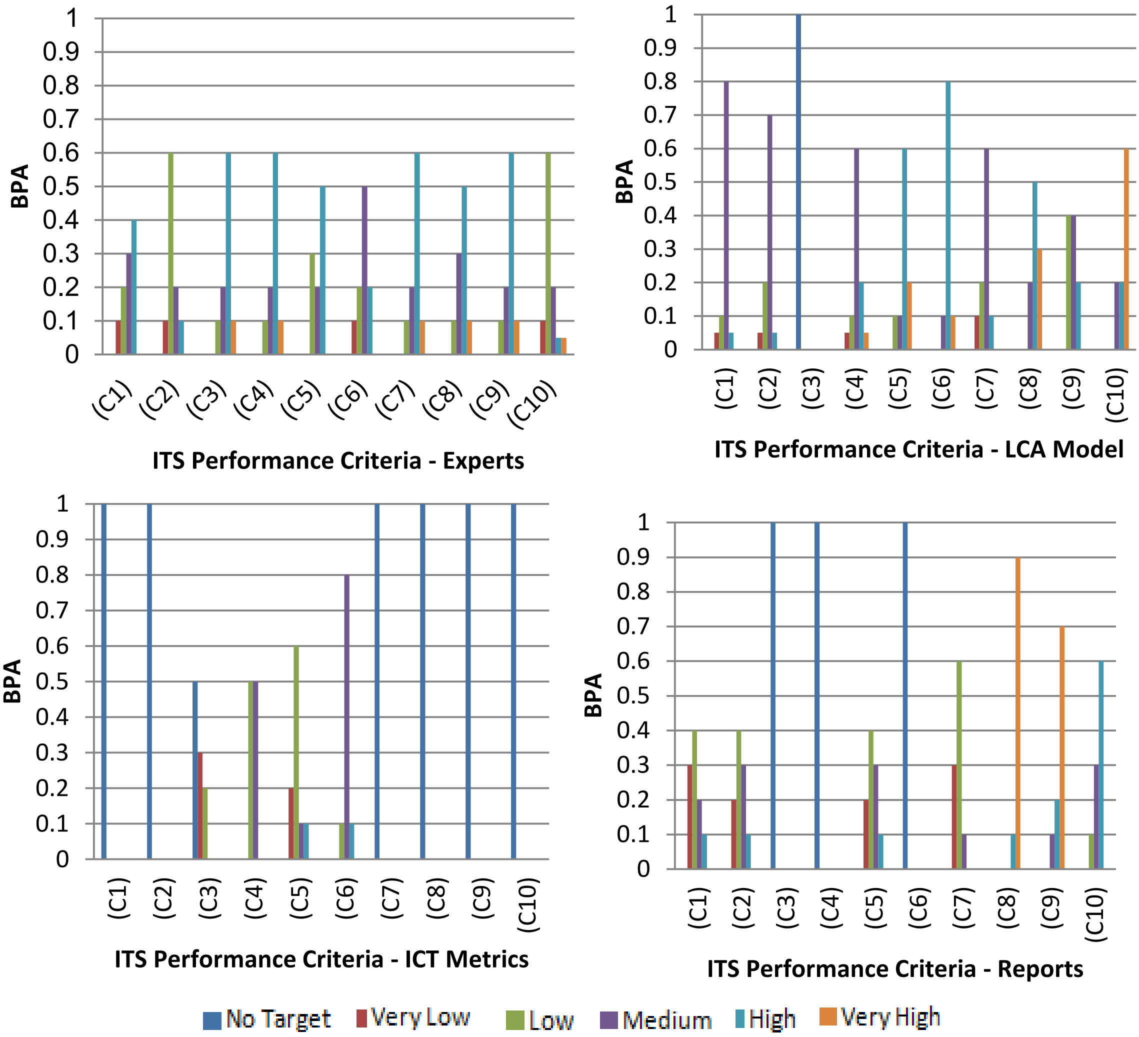


Figure 6.11: - ITS Sustainability BPA Assignments (Source: Kolosz et al, 2013a)

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 6.11

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

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

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

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

Table 6.10 presents the fusion[3] 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.

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

Table 6.10: - Data Fusion from information sources 1 and 2 (Source: Kolosz et al, 2013a)

$$k = 0.01 + 0.08 + 0.005 + 0.01 + 0.16 + 0.01 + 0.015 + 0.03 + 0.015 + 0.02 + 0.04 + 0.32 = 0.715 > 0$$

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:

$m_1^1 \oplus m_2^1(NT) = \frac{0}{0.285} = 0,\ m_1^1 \oplus m_2^1(VL) = \frac{0.005}{0.285} = 0.017, m_1^1 \oplus m_2^1(L) = \frac{0}{0.285} = 0.070$

$m_1^1 \oplus m_2^1(M) = \frac{0.24}{0.285} = 0.842,\ m_1^1 \oplus m_2^1(H) = \frac{0.02}{0.285} = 0.070, m_1^1 \oplus m_2^1(VH) = \frac{0}{0.285} = 0$

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

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 6.11.

	$m_3^1(NT) = 1$	$m_3^1(VL) = 0$	$m_3^1(L) = 0$	$m_3^1(M) = 0$	$m_3^1(H) = 0$	$m_3^1(VH) = 0$	$m_3^1(\Theta) = 0$
$m_1^1 \oplus m_2^1(VL) = 0.0017$	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 6.11: - Data Fusion from information sources 1, 2 and 3 (Source: Kolosz et al, 2013a)

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

---

3 Refer to Shafer (1973) and Beynon et al (2000).

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 6.12, 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 6.12: - Data Fusion from all sources (1, 2, 3 and 4) (Source: Kolosz et al, 2013a)

$$k = 0.0210 + 0.2526 + 0.0210 + 0.0028 + 0.3368 + 0.0280 + 0.0035 + 0.0140 + 0.0140 + 0.0017 + 0.0070 + 0.0842 = 0.791288 > 0$$

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 6.11. The bpa's of the criteria are illustrated in table 6.13 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 6.13: - BPA values following data fusion (Source: Kolosz et al, 2013a)

The overall performance ranking was then computed using the performance grades from chapter 5 (section 5.3.5, table 5.5) and distance to target weights that are specific to the M42. These were derived using the process outlined in section 5.3.5 and provided in Table 6.14 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	1388	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 6.14: - Distance to Target weights for the M42 case study (source: Kolosz et al, 2013a)

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

$$r_i \begin{cases} = r(NT) \times bpa(NT) + r(VL) \times bpa(VL) + r(L) \times bpa(L) \\ + r(M) \times bpa(M) + r(M) \times bpa(M) + r(H) \times bpa(H) + \\ + r(VH) \times bpa(VH) \times DTT \\ = 0.3 \times 0.02521 \times 0.5 + 0.5 \times 0.13445 \times 0.5 + 0.7 \times 0.80672 \times 0.5 \\ +0.9 \times 0.03361 \times 0.5 = 0.133948 \end{cases} \quad (6.3)$$

The overall sustainable performance ranking, distance to target weights and AHP were then calculated for the remaining 9 criteria as shown in Table 6.16.

6.4 Discussion and Sensitivity Analysis

Using the calculations shown in Table 6.15 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.

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 6.16, 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.

Performance Criteria	Calculation of Intelligent Transport Sustainability Index				
	GPR	*BPA's*	*DTT weighting*	*AHP*	*ITSI Value*
Scheme lifecycle emissions (C_1)	0.3 X 0.5 X 0.7 X 0.9 X	VL= 0.02521 L= 0.13445 M= 0.80672 H= 0.03361	X 0.5	X 0.100	0.033487
Road User Emissions (C_2)	0.3 X 0.5 X 0.7 X 0.9 X	VL= 0.01092 L= 0.52459 M= 0.45901 H= 0.00546	X 0.6	X 0.100	0.035508
GWP Data offset - IT certificates (C_3)	0.3 X 0.5 X	VL= 0.62791 L= 0.37209	X 0.1	X 0.100	0.002656
GWP per IT resource (C_4)	0.5 X 0.7 X	L = 0.07692 M = 0.92307	X 0.6	X 0.100	0.041077
Energy used per resource (C_5)	0.5 X 0.7 X 0.9 X	L= 0.66666 M= 0.05556 H= 0.27778	X 0.7	X 0.100	0.069028
Annual DCIE/PUE for data center (C_6)	0.7 X 0.9 X	M= 0.71428 H= 0.28571	X 0.8	X 0.100	0.060571
Roadside Energy Consumption (C_7)	0.5 X 0.7 X	L= 0.50000 M= 0.50000	X 0.5	X 0.100	0.030000
Acceptance (C_8)	0.9 X 1.0 X	H= 0.48076 VH = 0.51925	X 1.0	X 0.100	0.095193
Safety (C_9)	0.7 X 0.9 X	M= 0.85714 H= 0.14285	X 1.0	X 0.100	0.090000
Scheme Cost (C_{10})	0.7 X 0.9 X	M= 0.05263 H= 0.94736	X 1.0	X 0.100	0.099474

Table 6.15: - Intelligent Transport Sustainability Index calculations (Source: Kolosz et al, 2013a)

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 6.16: - Prioritised Sustainable Index Results (Source: Kolosz et al, 2013a)

From strongest to weakest (top to bottom in Table 6.16), 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.

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 6.17: - AHP and DTT Sensitivity Analysis (Source: Kolosz et al, 2013a)

A sensitivity analysis was carried out by varying the AHP criteria weights and the distance-to-target weights. Five scenarios were established (Table 6.17), 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 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.

Figures 6.11 and 6.12 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 CO_2 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.

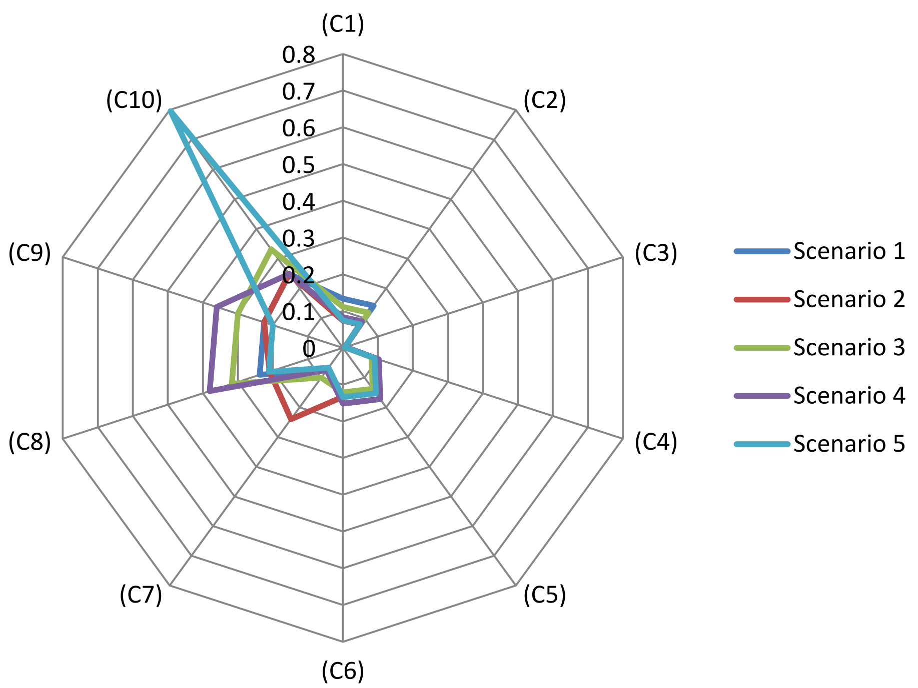


Figure 6.12: - Results of AHP Sensitivity Analysis (Source: Kolosz et al, 2013a)

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.

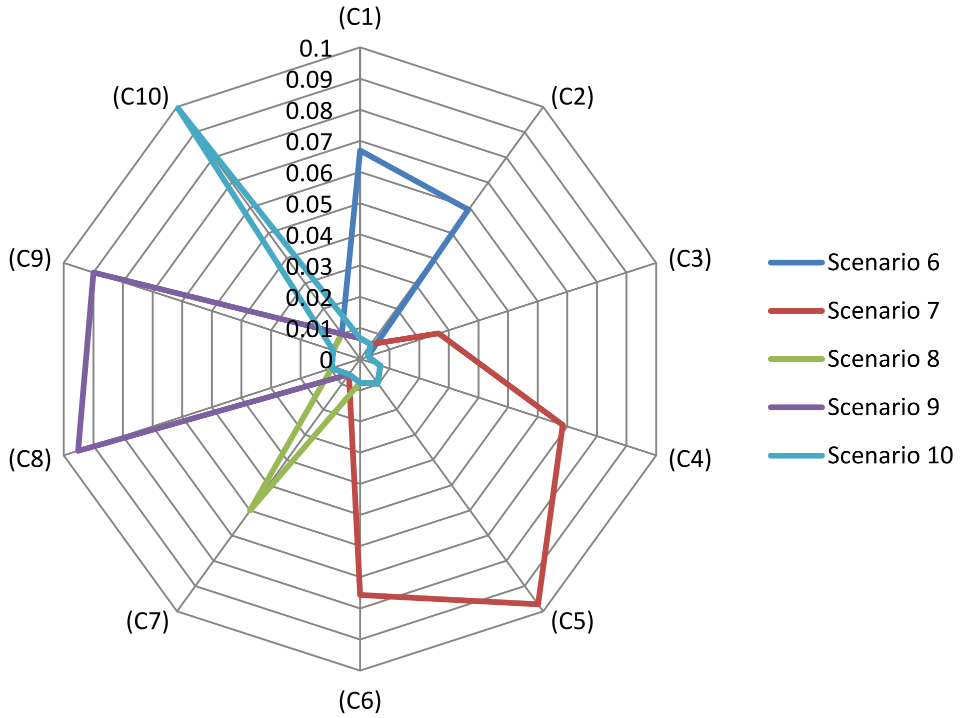


Figure 6.13: - Results of Distance-to-Target Sensitivity Analysis (Source: Kolosz et al, 2013a)

6.5 Summary

This chapter has discussed the evaluation of Active Traffic Management on the M42 highway using the EnvFUSION performance framework. The primary results indicate that the data center requires an environmental review in order to improve the performance of the ATM system. The next chapter presents the results from the second part of the study which illustrates a forecasting scenario of various future implementations of ITS technologies on the M42 and how performance can be estimated through changes within the current system configuration.

"A regulatory framework must be in place to ensure EU-wide implementation. Leaving the situation unchanged would lead to stagnation or even deterioration of the current conditions, resulting in an unchanged low level of market take-up and making it hard to achieve key policy objectives and to contribute to congestion reduction, road safety and environmental nuisance" (Psaraki et al, 2012).

Chapter 7 - Evaluation of Future Inter-Urban ITS Systems

This chapter introduces the second part of the study (assessing future sustainability performance) based upon projected estimation of ITS technologies up to 2050. The data collection procedure with regard to expected arrival of ITS services is presented and the steps to the development of the forecasting models are illustrated. The results of the study are then explored including a sensitivity analysis showing upper and lower bounds of the associated criteria. A Cost-benefit analysis was undertaken for Active Traffic Management, Intelligent Speed Adaptation and Automated Highway Systems and finally, performance indexing was performed based upon future targets.

7.1 Overview of the proposed framework

The following sections discuss the development of the EnvFUSION framework to project the delivery of ITS technologies up to 2050.

7.1.1 Overview

It is predicted that ICT will become increasingly ubiquitous, embedded at the user oriented level through in-vehicle and automated driver systems (Caravani et al, 2006a; Ferreira and d'Orey, 2012; Keqiang et al, 2012; Li et al, 2012). This transformation poses many challenges and naturally features high degrees of uncertainty the further the forecast occurs into the future. While some technologies are identified as having 'evolutionary' or marginal effects such as ATM (Bennett et al, 2010), other systems such as AHS with its 'platooning' function are more ambitious (Larburu and Sanchez, 2010). This research aims to provide a forecasting method to effectively account for these factors, providing a decision support tool so that decision makers can prioritize areas of improvement and evaluate ITS schemes using an integrated consequential modelling approach.

Following from the previous chapter, the second part of the study presents forecasted emissions reductions and socio-economic change for three key technologies of various scales for the M42 highway up to 2050. A cost benefit analysis is performed on each technology and interviews, the opinions of various experts and dynamically weighted targets provide input to a decision support model. Using a mathematical theory of evidence, a priority index is created to ascertain where overall sustainability gains and losses are anticipated.

7.1.2 Estimating the Performance of Future ITS technologies

The intial step in the framework was the selection of criteria for assessing the future sustainability of ITS. In practice this resulted from a process of literature study, brainstorming and peer review. As with the first part of the study, Experts within the academic community and road network operators then rated and prioritised the criteria based upon which performance group they viewed as the most important using an Analytical Hierarchy Process (Bernardon et al, 2011; Chan et al, 2013). AHP enables the user to establish weights for selected impact criteria through the use of pair-wise comparisons and is based upon three elements: the construction of a hierarchy, priority setting and logical consistency (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.

There are a total of four forecasting models used here, each belonging to a certain performance group representing a sub-area of 'sustainability'. The criteria which were proposed from the first study (Chapter 6) are generated from a specific forecasting model. The values of the criteria are compared with a Distance-to-target (DTT) method which allows for pre-defined future targets to be compared with the marginal values of the criteria during each timestep within the simulation (Weiss et al, 2007). These targets can be determined by local, regional and international government bodies and institutions. Whilst DTT was originally an LCA method to evaluate and prioritize the different environmental impact categories, in this paper it has been expanded to incorporate a range of sustainability aspects and modified to give an aggregated score, whilst AHP provides prioritization of the criteria. The reduction targets can be achieved by improvements in technology. Using a modified version of the Distance-to-target method used by Lin (Lin et al, 2005), the weighting and percentile of the initial performance state is calculated via

$$DTT_{(initial)} = ASB_{(initial)} - FST_{(initial)} \tag{7.1}$$

or if the target should be of a higher value, (7.1) is inverted. With $DTT_{(tbase)}$ being the distance-to-target value dependent on the context of the criteria in focus, $ASB_{(tbase)}$ the apparent level of sustainability burden and $FST_{(tbase)}$ the future sustainability target. sustainability has been referred to in this context as a subjective value which takes into account all facets of evidence in the form of a sustainability index (representing the group of criteria). The following equations are used to calculate the performance of criterion with negative (7.2) or positive (7.3) distance to target values.

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{ASB_{(tyear)}} X\ 100 \tag{7.2}$$

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{FST_{(tyear)}} X\ 100 \tag{7.3}$$

7.1.3 Forecasting using Key Performance Indexing

As with the previous study, the data (basic probability assignments and mass functions) are collected for the criteria from various sources including experts, IT environmental reports, a cLCA model and direct measurements. It should be noted for the forecasting element that sources use their own grading system and will be able to subjectively rate performance using this method as in Chapter 6. Table 7.1 illustrates a performance ranking in order to assign belief vectors to the BPA values depending on the result of the distance to target method and the data fusion process used by D-S theory.

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

Table 7.1: - Key Performance Indexing for Forecasting Assessment (Source: Kolosz et al, 2013b)

7.2 Model Behaviour and Data Collection

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

7.2.1 Vehicle Socio-Environment Model

The vehicle model uses a series of speed emissions curves that were developed in 2009 (Boulter et al, 2009). Together with forecasts of national traffic levels and vehicle speeds these are used to predict future quantities of fuel use and road traffic emissions up to 2050. In order to understand the level of offset ITS schemes will bring to a given highway, data was aggregated from a series of speed emission curves (Boulter et al, 2009) together with forecast trends (National Atomospheric Emissions Inventory, 2012) and average vehicle speeds.

Data for traffic volume was taken from the UK Department for Transport Average Annual Daily Traffic Flow or AADF (based on the average vehicles per day) for the length of highway. AADF's were created from a number of manual traffic count points by the DfT. The raw data were then combined from a network of automatic traffic counters (ATC) to calculate a series of AADF's (Annual Average Daily Flows) for each count point (7.4). To calculate traffic volume, AADF's were combined with the link length and multiplied by the number of days in the year.

$$Traffic_{CP} = AADF_{CP} \times Length_{link} \times 365 \quad (7.4)$$

In Figure 7.1, using linear regression, traffic growth is projected via the percentage of expected new vehicle registrations within the west midlands region and remains in-line with the rate of national highway traffic growth (49% in 2035 extrapolated to 78.4% by 2050).

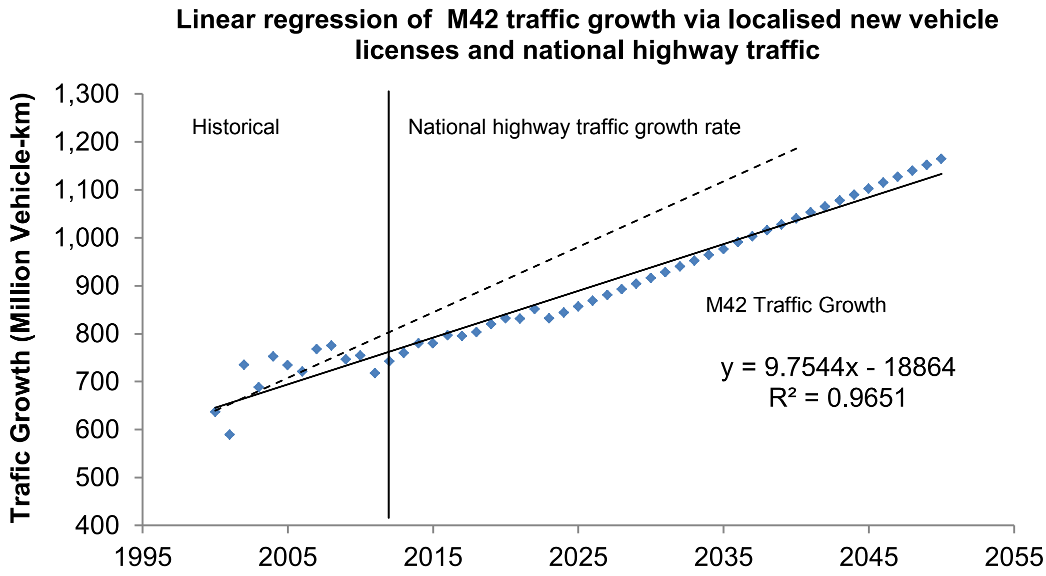


Figure 7.1: - Linear regression of traffic growth at M42 junction 3a-7

Critically, the increase in traffic growth up to 2050 had to also be validated against the maximum capacity of the M42 highway. According to Chase and Avineri (2008) in the UK, highways are designed to carry between 1100 vehicles (rural) and 1900 vehicles (urban/motorway) per hour per lane (veh/h/l) for both directions, although Psaraki et al (2012) indicates that this figure may actually vary from 1800-2400 veh/h/l depending upon the behaviour of the driver. Peak flow data was collected from the M42 12 month monitoring and evaluation report (Sultan, 2009). Figure 7.2 illustrates the projected morning and afternoon peak traffic demand based upon a Tuesday, Wednesday and Thursday using localised traffic growth up to 2050. Junction J5-6 was selected as it has the longest link length therefore the benefits would be more clearly visible. It should be noted that the maximum vehicle capacity of the highway would also increase with the gradual introduction of ITS technologies as discussed below. The black dotted lines represent the upper and lower bounds of the estimated traffic capacity.

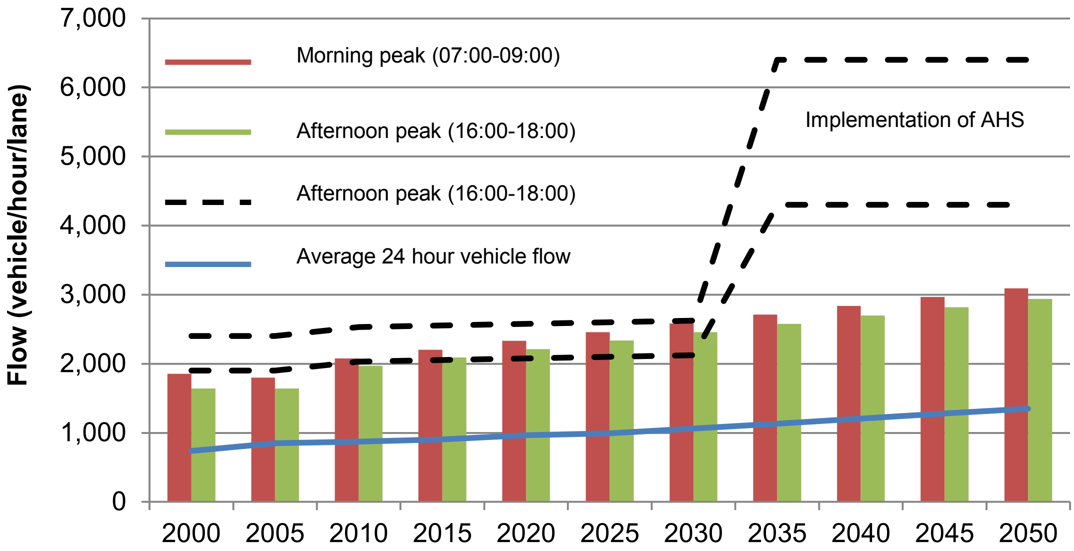


Figure 7.2: - Projected peak traffic demand and capacity (Northbound J5-J6)

ITS services deliver a variety of benefits which allow the capacity of a road to improve (Chase and Avineri, 2008; Psaraki et al, 2012). According to Sultan (2009) ATM on the M42 has improved vehicle capacity by around 7% or an equivalent of 400 extra vehicles. ITS technologies such as ISA keeps traffic flow more homogenised and total throughput may increase by approx 5%. Capacity improvements of about 7–8% or 1900-2600 veh/h/l in comparison with manual driving conditions have been reported because of the decrease of headway. This depends greatly on the penetration rate and the headway setting (Zwaneveld and Van Arem, 1997) and is reflected within Figure 7.2 as a gradual improvement from 2010 up to 2045 where it is estimated that ISA would become mandatory (Lai et al, 2012). Deployment of AHS is expected to increase capacity in two ways. It reduces distances between fully automated vehicles until they reach the minimum safe distance. This results in more vehicles per lane and in addition, stabilises the traffic flow. Traffic equilibrium can be reached avoiding stop-and-go driving and the inefficiencies caused by inattentiveness, merging, weaving and lane changing (Bergenhem et al, 2010; Al-Kaisy and Durbin, 2011). The capacity benefits offered by AHS depend on the platoon configuration. Key parameters are the platoon size and the inter-vehicle and inter-platoon separations. Platoon sizes may range from 5 to 20 vehicles. To maximise throughput it is desirable to form platoons that are reasonably long (Hall and Chin, 2005a). AHS is expected to give significant capacity improvements of between 4300 to 6400 veh/h/l and is anticipated to arrive in approximately 2035 after the ATM service is removed due to traffic management services being provided through in-vehicle systems. Finally, it should be noted that traffic growth may be reduced via governmental legislation such as the electronic tolling of the M42 (Iseki and Demisch, 2012) as well as the anticipated development of the new high speed rail link which would connect London to the West midlands region and is expected to arrive in 2026.

Figure 7.3 illustrates the estimated number of vehicle categories up to 2050.

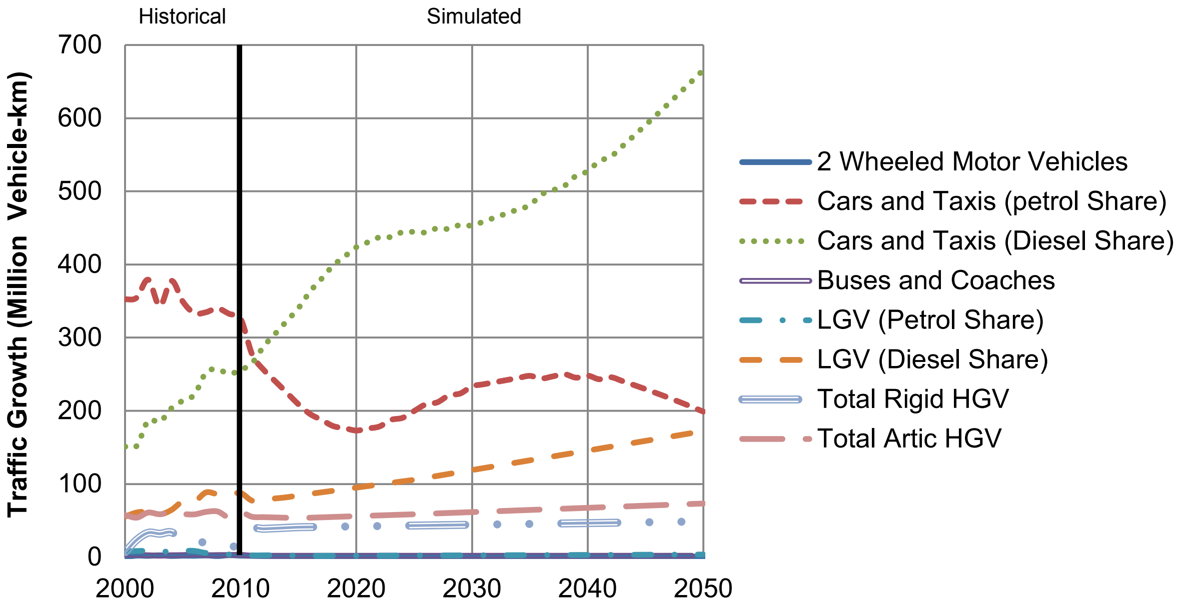


Figure 7.3: - Estimated number of vehicle categories on M42 junction 3a-7 up to 2050 (Source: Kolosz et al, 2013b)

Emission curves were taken from the Transport Research Laboratory (Boulter et al, 2009). TRL was commissioned by the Department for Transport to review the approach used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles and to propose new methodologies. Raw test data were grouped into a number of vehicle categories, plotting them against the average speed of the test cycle and fitted to a common polynomial expression of the form:

$$EF\left[\frac{g}{km}\right] = \frac{k}{x}\left(a + \sum_{i=1}^{6} \beta_i x^i\right) \qquad (7.5)$$

where a is a constant and β_i, represents the i'th coefficient of x, the speed in kph for a particular Euro standard. The factors are given for a range of different vehicle classes, sizes and fuel types and for each legislative Euro standard from pre-Euro up to Euro 6/VI. For simplification purposes, all factors given are normalised to 50,000km accumulated mileage, although in some cases, scaling factors for emission degradation and fuel quality effects were applied on selected vehicle types As an example, for year y the emission curve for each medium sized petrol car Euro standard is given by:

$$EF_{ye} = D_{ye}.S_{ye}.S_e.(a_e + b_e.x + c_e.x^2 + d_e.x^3 + e_e.x^4 + e_e.x^5 + e_e.x^6)/x \quad (7.6)$$

These equations can be aggregated to a single expression weighted by the proportion of vehicle kilometres done by each euro standard via:

$$EF_y = R_{y0}.EF_{y0} + R_{y1}.EF_{y1} + R_{y2}.EF_{Y2} + R_{yn}.EF_{yn} \quad (7.7)$$

where R_{yn} is the proportion of petrol car km by Euro *n* (1,2,3 etc) vehicles in year y. EF_{y1}, EF_{y2} ….EF_{y50} are the emission factors for Euro 1, Euro 2 …. Euro 6 medium-sized petrol car in year y, given by Equation (4), leading to the single expression:

$$EF_y = (A_y + B_y.x + C_y.x^2 + D_y.x^3 + E_y.x^4 + F_y.x^5 + G_y.x^6)/x \quad (7.8)$$

where:

$$A_y = R_{y0}.D_{y0}.S_{y0}.K_0.a_0 + R_{y1}.D_{y1}.S_{y1}.K_1.a_1 + R_{y2}.D_{y2}.S_{y2}.K_2.a_2 + R_{y3}.D_{y3}.S_{y3}.K_3.a_3 + R_{y4}.D_{y4}.S_{y4}.K_4.a_4 + R_{y5}.D_{y5}.S_{y5}.K_5.a_5 + R_{y6}.D_{y6}.S_{y6}.K_6.a_6 \quad (7.9)$$

$$B_y = R_{y0}.D_{y0}.S_{y0}.K_0.b + R_{y1}.D_{y1}.S_{y1}.K_1.b_1 + R_{y2}.D_{y2}.S_{y2}.K_2.b_2 + R_{y3}.D_{y3}.S_{y3}.K_3.b_3 + R_{y4}.D_{y4}.S_{y4}.K_4.b_4 + R_{y5}.D_{y5}.S_{y5}.K_5.b_5 + R_{y6}.D_{y6}.S_{y6}.K_6.b_6 \quad (7.10)$$

$$n_y = R_{y0}.D_{y0}.S_{y0}.K_0.c + R_{y1}.D_{y1}.S_{y1}.K_1.c_1 + R_{y2}.D_{y2}.S_{y2}.K_2.c_2 + R_{y3}.D_{y3}.S_{y3}.K_3.c_3 + R_{y4}.D_{y4}.S_{y4}.K_4.c_4 + R_{y5}.D_{y5}.S_{y5}.K_5.c + R_{y6}.D_{y6}.S_{y6}.K_6.c_6 \quad (7.11)$$

The coefficients A-G are weightings of the individual coefficients a-g for the different Euro standards from pre-Euro 1 (denoted as Euro 0) to Euro 6 according to the fractions in the fleet in year y. Equation (6) and the coefficient A_y-G_y denote the expression in this example of the fleet-weighted emission curve of a medium-sized petrol car in year y. A further weighting is required to derive a single expression for all petrol cars in years according to the mix of small, medium and large petrol cars in the fleet, given in Table 4 (<1400c, 1400-2000cc, >2000cc). Thus the coefficients A_y are calculated for small, medium and large petrol cars and weighted according to:

$$Ay, petrol\ cars\ = 0.383. Ay, small\ +\ 0.477. Ay, medium\ +\ 0.141. Ay, large \quad (7.12)$$

and similarly for the coefficient B_y to G_y. The coefficients $A_{y,\ petrol\ cars}$ – $G_{y,\ petrol\ cars}$ calculated in this way are the coefficients a-g in spreadsheet form for each year y. Coefficients were calculated in the same way for all other main vehicle types, pollutants and years. Emission Factors were recorded based upon regulated pollutants including CO (Carbon Monoxide), NOx (Nitrogen Oxide), HC (Hydro-carbons), PM (Particulate Matter) and uCO_2 (Ultimate Carbon dioxide emissions based upon direct fuel consumption). While unregulated pollutants emission factors have been developed by TRL for use in the NTM, they were excluded in this study due to two key points. Firstly, very little work has been carried out by the literature to determine the estimated emissions reduction using unregulated pollutants for ITS services. In addition, their low level of accuracy and ambiguity within the methodology of the emission factors may give inaccurate and unacceptable results and this has been noted by Boulter (2009).

> "There were a number if inconsistencies and general difficulties associated with the data for unregulated pollutants. It was evident that some of the data could not be used to develop emission factors, and some concerns were raised about the validity of ostensibly 'correct' data." (Boulter et al, 2009).

For EnvFUSION, all emissions were characterised into CO_2 equivalency using the Global Warming Potential methodology as carried out in the first part of the study in Chapter 6. Note that other vehicle technologies such as hybrid, bio-diesel and electric are not included in the results due to very limited market data, although by 2040 it is assumed that these vehicles will begin to play a more dominant role as the Euro 6 standard declines in market share when applied to conventional technologies.

Curves for ‘ultimate’ CO2 emissions were derived directly from the fuel consumption by converting the units from litre/100km to g fuel/km and applying a simple conversion factor based on the carbon content of petrol and diesel fuels. The fuel carbon contents used in the Greenhouse Gas Inventory are provided by the UK Petroleum Industry Association and remain constant in all years at 85.5% for petrol and 86.3% for diesel (UKPIA, 2004). These figures refer to the percentage carbon content by mass, in other words 100 g diesel comprises 86.3 g carbon. The mass density of fuel is 1.199 litre per kg fuel for diesel and 1.361 litre per kg fuel for petrol (BERR, 2008). From this it follows that the factors for converting fuel consumption in litres/100km to CO_2 emissions in gCO2/km were: Petrol: 23.03 Diesel: 26.39

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

7.2.2 Road-side Infrastructure Model

The road-side infrastructure model assesses the embedded and operational emissions of a given ITS technology. As time progresses, new technology may become available which allows for improvement in manufacturing technologies, although this does not remove the embedded emissions completely.

Projected cradle to grave embedded emissions were produced by the model based upon expected technology improvements through time. In order to make the cLCA data set manageable, only the 7 dominant materials in Inter-Urban ITS systems were used. These include aluminium, copper, electrical equipment, plastics, reinforced concrete, steel and toughened glass.

Figure 7.4 represents a Stock and Flow model of the aluminium cLCA feedback. All materials used within the model possess their own stock and flow model and they were developed using the VENSIM system dynamics modelling software.

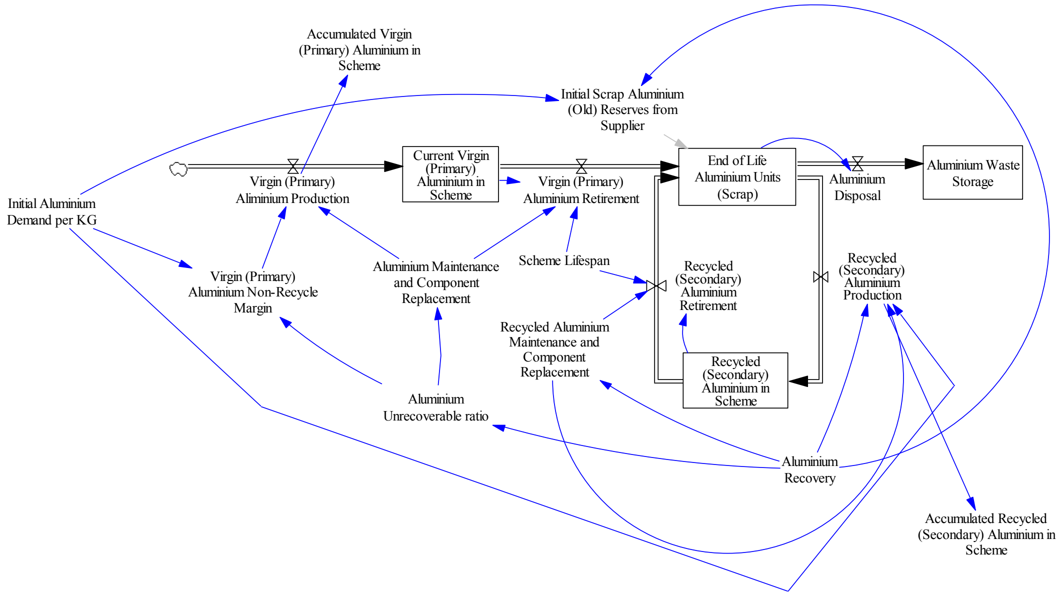


Figure 7.4: - 'Stock and flow model' representing aluminium cyclic cLCA feedback

Both Primary (Virgin) and Secondary (Recycling) processes are modelled and their cumulative share in the production process is determined by the average European share (UK where available). This data was compiled from various sources including the Ecoinvent database (Frischknecht and Rebitzer, 2005) industry reports and academic literature. For example, for 2011 in Europe, aluminium possesses a mean recycling rate of approx 54%, meaning that 54% of the demand is processed from end-of-life aluminium scrap (5% energy usage) as opposed to energy intensive mining and processing of bauxite ore with further gains in landfill reduction and export of raw aluminium (European Aluminium Association, 2011). As the recovery ratios are marginal, a series of confidence intervals were applied to determine the uncertainty along the time-line in the form of upper and lower boundaries.

Where available, a primary (virgin) and secondary (recycling) emissions factor for each process was applied to the materials using the global warming potential methodology as stipulated by the Intergovernmental Panel on Climate Change's CO_2 conversion factors (Solomon, 2007). Each emissions factor takes into account the full cradle-to-grave process of all greenhouse gas substances including energy and the equipment used to convert raw materials into a finished product. Table 7.2 illustrates the LCA characteristics of all 7 materials under analysis with recycling set to the European average recovery rates from end-of-life. Primary and secondary processes are shown where available.

Material (Year of Data) and Source	End-of-Life Recovery Ratio (%)	GWP per KG Primary/Secondary (CO_2eqv)
Aluminium (2011) (European Aluminium Association, 2011; Graedel et al, 2011)	42-70 (54 Mean)	15.9/3.7
Copper (2010) (Graedel et al, 2011; International Copper Study Group (ICSG), 2011)	45-68 (57.5 Mean)	3.68/3.62
Electrical Equipment (Graedel et al, 2011; UK Environment Agency, 2012)	40-60 (50 Mean)	275/x
Plastics (2010) (Plastics Europe, 2011)	20-70 (45 Mean)	4.8/x
Reinforced Concrete (2013) (Crawford, 2009; Minson, 2013)	30-50 (40 Mean)	0.12/x
Steel (2011) (Graedel et al, 2011)	70-90 (80 Mean)	2.08/0.42
Toughened/Tempered Glass	0-14 (7 Mean)	1.09/0.47

Table 7.2: - Material Emission Characteristics

As time progresses, cleaner energy technologies will begin to reduce the GWP value of the electricity output (in kWh-CO2eqv). Although the details of such technologies arise from the microscopic level, they will directly affect the system as exogenous variables. The data was collected from UK GHG conversion factors (AEA, 2011) and consists of the cumulative total of consumed electricity (including generated and electricity transformation loss) of direct emissions consisting of CO_2, CH_4 and N_2O from the combustion of fuel in power stations. Imported net electricity from abroad is also included with the mainline input from France and eventual output to Ireland. As GWP has only been recorded from 1990 onwards this is a very limited data set, therefore a power regression trend was modelled to simulate the gradual de-carbonisation of the UK energy grid (Figure 7.5a).

The selection of the power regression was two-fold, its R-square value (goodness of fit) was highest (72%) and they were able to represent a gradual decrease in emissions compared to a linear trend which assumed de-carbonisation would equal zero before 2050. Polynomial and logarithmic trends were discounted completely due to the shape of the trend being unrealistic despite producing a higher R-squared value of 91%. Figure 7.5b displays the 95% confidence interval for projected de-carbonisation for 2013 onwards using a power regression trend-line.

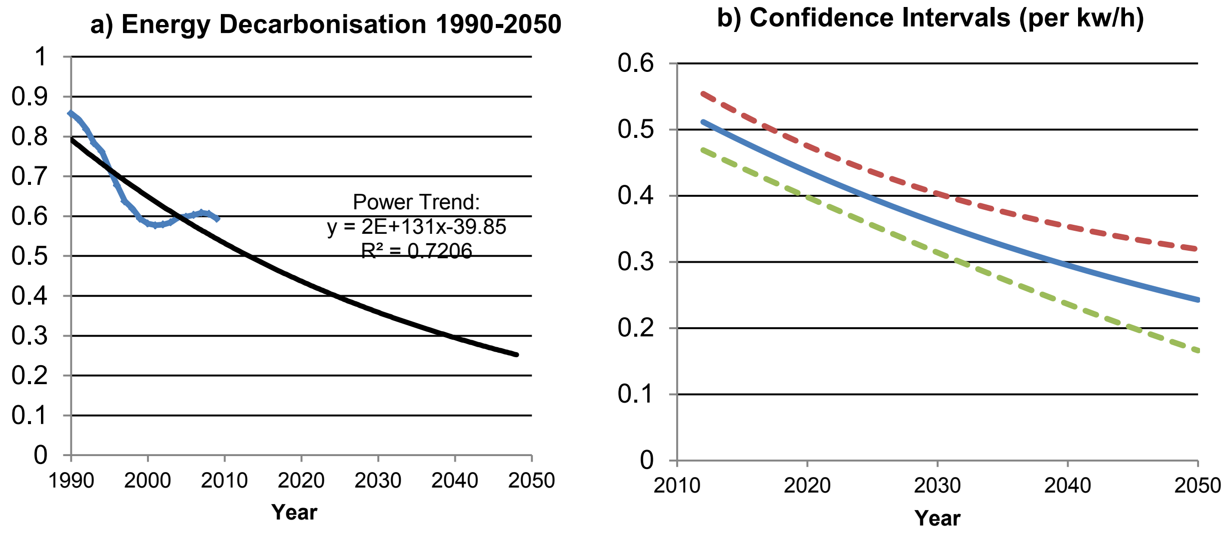


Figure 7.5: - a) UK Energy Grid De-Carbonisation (1990-2050) and b) Forecasted Emissions Factor (Power Regression) (Source: Kolosz et al, 2013b)

In order to estimate the emissions of ICT technology within current and future ITS systems, the data center was analysed based upon a number of criteria. To calculate the operational emissions of the ICT data links, various energy efficiency metrics and indicators were adopted from the literature. The four main criteria for assessing the performance of ICT operational emissions are KG of GWP covered by renewable energy certificates, KG of GWP per IT task or resource focuses on the GHG emissions at the software level (or hardware if data not available), Energy used per task or resource indicates the shared resources towards managing the ITS technology on the highway and is measured in kW/h and finally, the annual Power Usage Effectiveness or Data center infrastructure efficiency (Jaureguialzo, 2011).

Depending on the type of technology and the year that is concerned, there may not be a defined centralized data center or no fixed road-side infrastructure. For example, Vehicle-2-Vehicle is a form of communication within the Vehicular Network field. The vehicle sends data to other vehicles which can be used to manage safety and inform other road users of oncoming traffic as well as the current capacity of the traffic network (Bell, 2006a; Boukerche et al, 2008; Fuchs and Bankosegger, 2009; Hamouda et al, 2009). However, the communication is handled largely via the vehicles on-board systems which in turn is powered by their battery. For the purposes of this study, in-vehicle systems will become standardized by around 2030 making the ATM road-side technology obsolete and it will be removed from the network.

7.2.3 Cost Model

The criteria 'Scheme cost' is based upon the economic procurement of infrastructure and systems to operate the ITS scheme as well as transport appraisal. To determine the cost of ATM, the total capital costs per KM of highway were used. For ISA and AHS this includes the cost to procure in-vehicle equipment.

For ISA, technology depreciation is illustrated to show the reduction of costs over time as the technology becomes standardised although this is not available for AHS due to the forecast only being available over 15 years which is considered too short to determine in terms of market impact. A Cost-Benefit Analysis was applied to ISA and AHS technologies under scope in section 7.4.

Table 7.3 illustrates the breakdown of costs used to procure the equipment and operational running of the three technologies as given in the literature (Lai and Carsten, 2012; Psaraki et al, 2012).

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

Table 7.3: - Unit Costs of ITS equipment and Maintenance (Source: Kolosz et al, 2013b)

7.3 Main Results

The results and analysis presented here are based upon the methodology outlined in Chapters 3 and 5 and in Section 7.2. The results consists of the impact assessment allocated to the environmental, energy and socio-economic performance groups. In order to deliver the impact assessment of the three technologies, various assumptions were made. Firstly, it was estimated that the ATM infrastructure would possess a lifespan of approximately 25 years, meaning that all systems related to ATM will cease by 2030 as well as the removal of the road-side infrastructure. This includes the removal of most ICT data connections from the local traffic control centre. At 2030, in-vehicle systems will become mandatory therefore the road-side infrastructure will be stripped due to communications from the road network operator being delivered within the car. ISA is simulated based upon the type of system architecture and three different modes of operation (Advisory, Voluntary and Mandatory). According to Carsten and Tate (2005) initial proposals of ISA were to develop roadside DSRC (Dedicated Short Range Communication) beacons to assist vehicles in identifying areas where the correct speed limit is applied. However, the literature dictates that a more autonomous system where vehicles communicate via satellites to identify location with on board digital mapping software was preferred. This means that additional ITS roadside infrastructure can be negated (the approach adopted in this study).

The market forecasts were based upon an authority driven scenario in (Lai et al, 2011) where full market penetration of 'Advisory' Intelligent Speed Adaptation is expected to be delivered in 2020 with gradual penetration of 'Voluntary' thereafter. By 2045, this scenario forecasts that the 'Mandatory' function which restricts the driver to exceeding the maximum speed limit will be required by law. These three modes have influence not only on emissions but also safety and cost elements of the model under investigation.

Automated Highway Systems, although in theory possessing rich environmental and socio-economic benefits are more difficult to quantify in terms of market penetration due to uncertainty in technological and policy issues, although numerous studies have been performed (Psaraki et al, 2012). AHS was simulated with the assumption of one car only lane being allocated to platooning in 2035. This is due in part to high performance degradation when mixing different types of vehicles (Kanaris et al, 1997). It is expected that platooning will allow maximum throughput capacity of the highway to increase from between 1800-2400 to 4300-6400 vehicles per lane per hour, although it is expected some form of infrastructure is still required to monitor the system. The next section illustrates the results within the environmental social, energy and economic frames.

7.3.1 Environmental Results

As new technology standards evolve, the emissions of vehicles reduce over time. There is a sharp decline in road user emissions at 2008 within the historical data set. This is assumed to be a combination of the introduction of the Euro 5 emissions standard being introduced alongside the initial onset of the economic recession as the number of freight vehicles declined. ATM saves a total of 99 kilo-tonnes of CO_2 equivalency over its lifespan. ISA is expected to have an impact of 90 kilo-tonnes of CO_2 equivalency saved, although this figure is lower than ATM due to market share not having a significant impact until 2022. As predicted, there is a significant level of emissions reduction when AHS is active with a total saving of 280 kilo-tonnes of CO_2 equivalency. It should be noted that the effects of emissions reduction post-ATM will not weaken due to the introduction of driver assisted systems, offering a similar set of services in terms of traffic management. This assumption was included within the model. The environmental group results for the M42 junction 3a-7 are illustrated in Figure 7.6. IT emissions (Figure 7.6a) and road-side energy consumption (Figure 7.6b) were simulated based upon the gradual de-carbonisation of the energy grid. In Figure 7.6c, e and f, the green line indicates the impact of the ITS systems on emissions while the blue line represents the emissions trend without the assistance of technology. For this study it was not possible to obtain sufficient data to determine the KG of GWP per IT task or resource for a sufficient forecast. This would require new metrics and measuring systems for assessing energy consumption at the software level which at this moment in time is unavailable. Instead, the results are illustrated at the hardware level as shown in the top left of Figure 7.6a. The expected introduction of the ITS technologies are displayed as well as the expected end date of Active Traffic Management. Upper and lower data boundaries are displayed in red (negative scenario) and green (positive scenario). Roadside infrastructure emissions (Figure 7.6d) shows the residual embedded emissions from the manufacturing, installation and removal process of ATM. In addition, the maintenance of the electronic equipment is undertaken in 2015 and 2025 where the expected failure of electronic units are replaced like for like. It was assumed that after 2030 the emissions are zero due to the removal of the ATM infrastructure and will remain so due to the full deployment of driver assisted systems and in-vehicle communication.

Figure 7.6 a) IT Emissions from Data Center

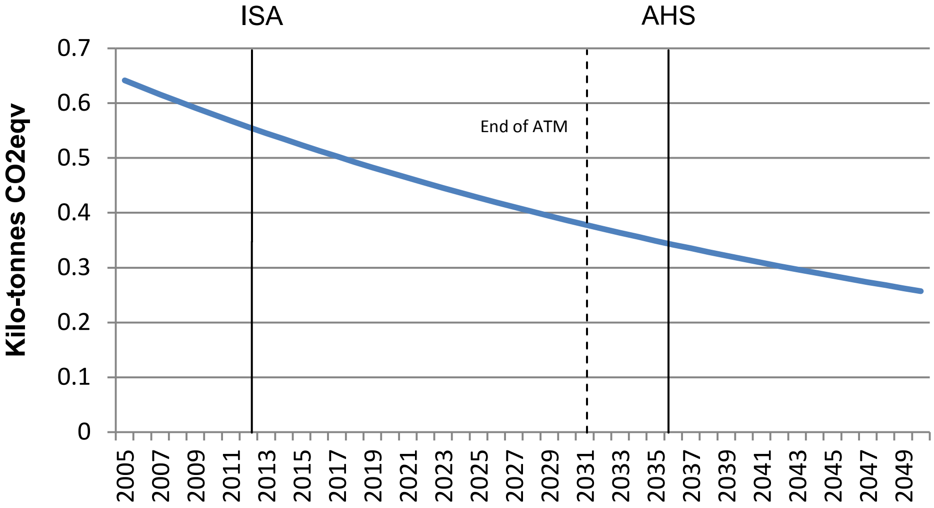


Figure 7.6 b) Road-side Energy Consumption

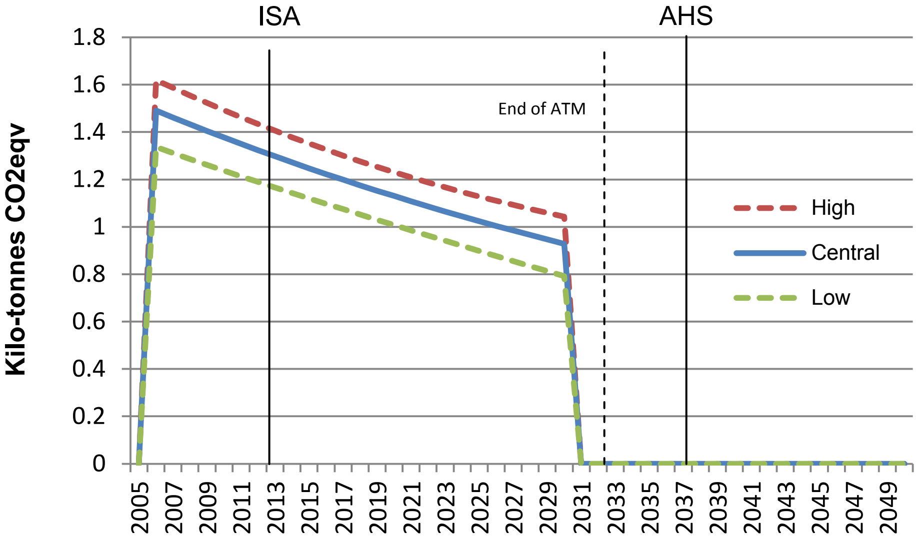


Figure 7.6 c) Road User Emissions

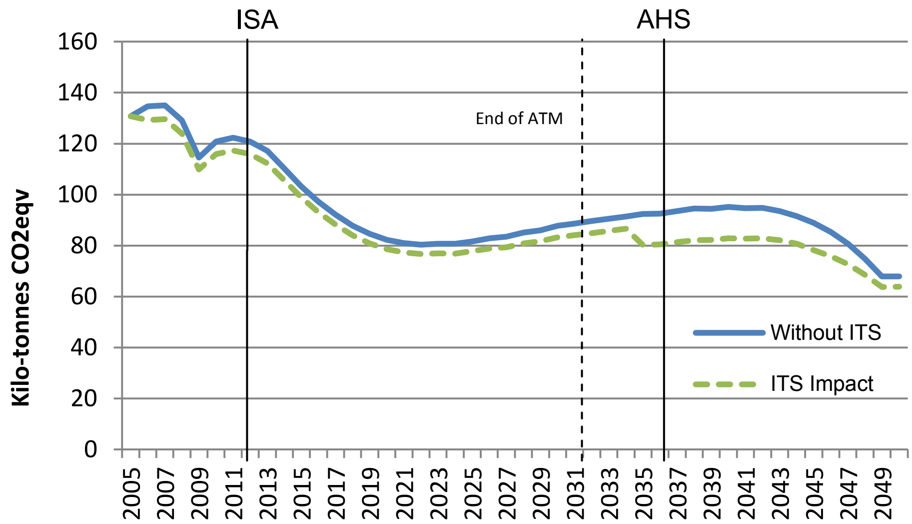


Figure 7.6 d) Embedded Infrastructure Emissions

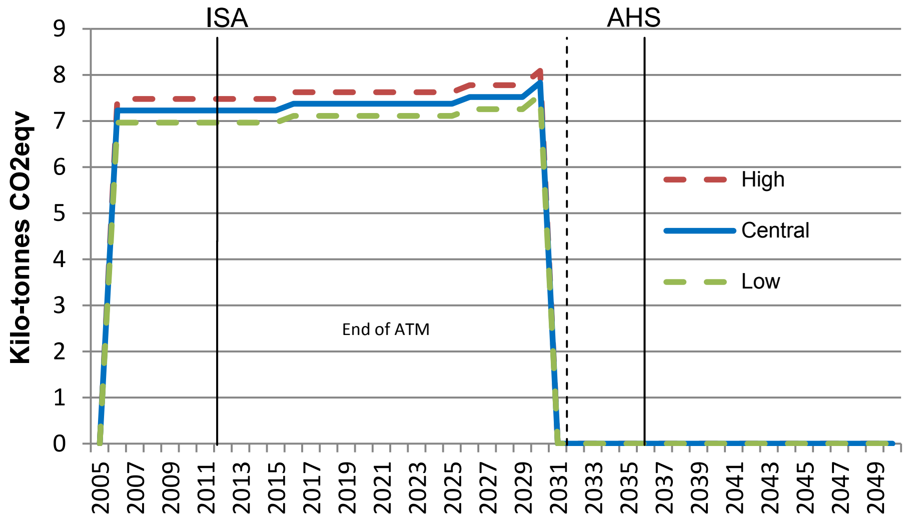


Figure 7.6 e) Diesel Fuel Consumption

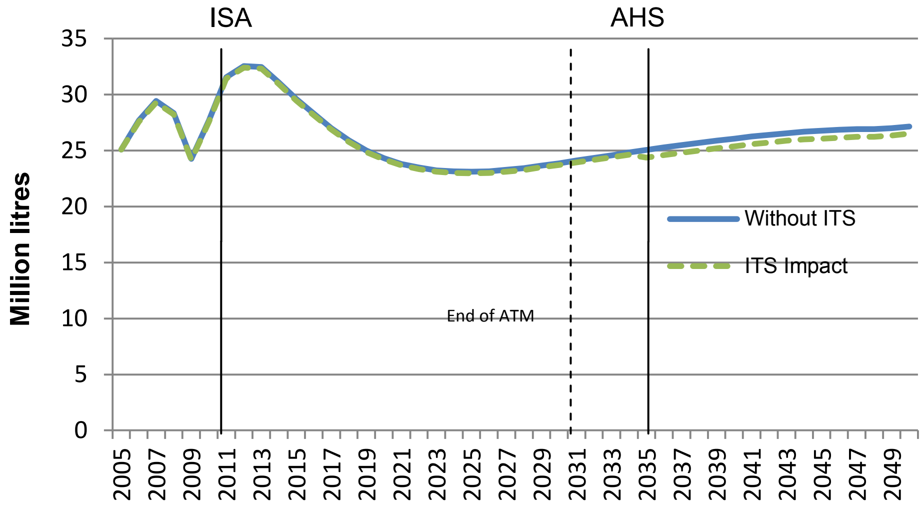
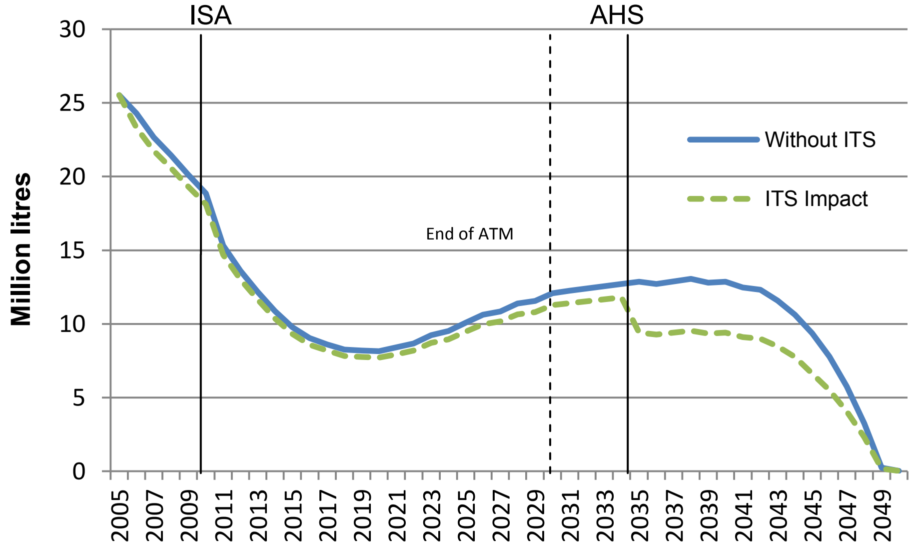


Figure 7.6 f) Petrol Fuel Consumption



7.3.2 Energy Results

Results of the energy consumption of the road-side equipment and ICT data center were taken into account for the model. ATM consumes high levels of energy due to the road-side infrastructure compared with other technologies. In addition, the IT data center draws energy in order to assist in the control of the system. Once again, measuring the impact of the ICT data links per task or resource cannot be undertaken due to insufficient data, therefore energy is determined for the data center as a whole. Table 7.4 illustrates the energy consumption of the ATM scheme. Note that for the energy consumption of the road-side infrastructure this does not include the additional energy costs of enforcement areas (i.e. where speed is controlled via surveillance cameras and motorway indicators). A detailed overview of the energy consumption for ATM is available in Appendix A.

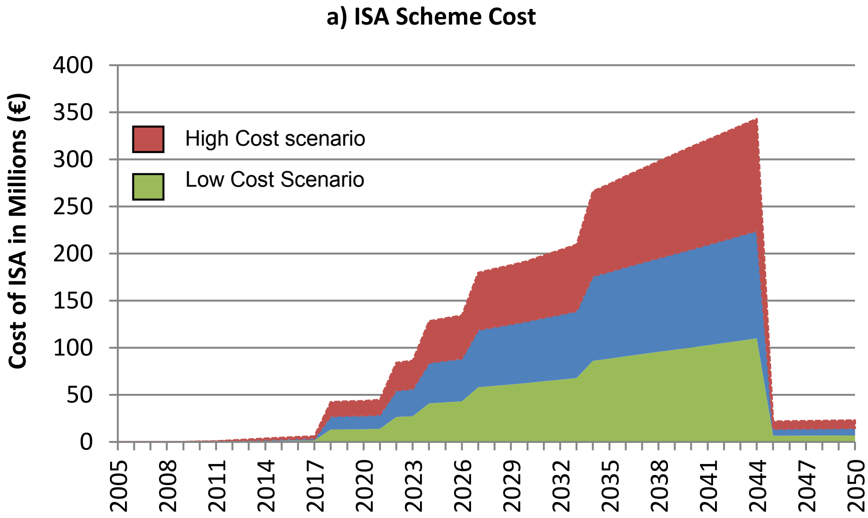
Infrastructure Components	Energy (mW per annum)	Lifespan (25 years)	Whole Scheme + Lifespan
Equipment Cabinets	41.39	1,034	20,363
NRTS Load (Network)	19.71	492.7	16,160
Message Sign (Mark 4)	2.394	59.86	3,926
Speed Indicator (AMI)	0.364	9.115	2,391
CCTV	5.046	126	8,265
ICT Data Center	185.7	4,643	4,643
TOTAL	254.6	3,742	43,271

Table 7.4: - Energy Consumption of ATM

7.3.3 Socio-Economic Results

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

In order to estimate the cost of the future technologies, statistics on the number of licensed vehicles within the West Midlands region were collected as well as the rate of new vehicles per annum. The expected traffic growth was multiplied against the procurement and operational costs as illustrated in Table 4. Upper and lower data boundaries were applied to ISA to determine the spread of possible costs with the assumption that the voluntary/mandatory technologies would gradually become more expensive depending upon the market share and/or supply of the electronic components required to produce the on-board equipment. There was insufficient data available on AHS systems to apply these assumptions, due to a lack of technological maturity in the final product.



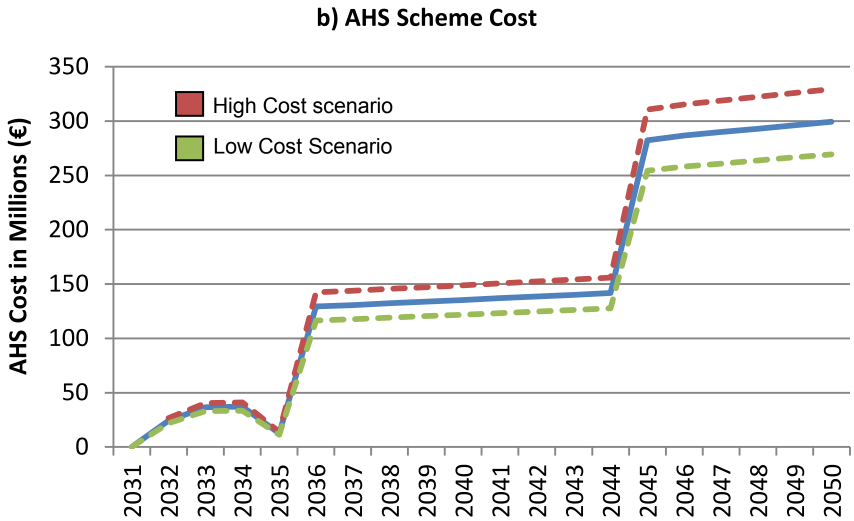


Figure 7.7: - Scheme Cost of ISA (a) and AHS (b) technologies (Source: Kolosz et al, 2013b)

For ISA (Figure 7.7a) according to the 'authority scenario' proposed by Lai et al (Lai and Carsten, 2012) a total of between 1-1.4 billion euros would be spent on the rollout of initially 'Advisory' technologies hitting a peak of 92% market share in 2021 with over 220 million euros invested in technology procurement. During this period 'Voluntary' technologies are expected to possess a market share of 8%. By 2045, 'Mandatory' technologies would be enforced by government legislation. The investment for AHS (Figure 7.8b) would be 2.6-3 billion euros overall from a start date of 2035. For the purposes of this study, it was assumed that an initial trial of AHS technology would take place on the M42 stretch of highway, with the technology in some manufactured vehicles from 2032. This assumption is displayed visually in Figure 75b. The overall safety for the M42 is expected to improve substantially (Table 7.5). The number of slight accidents is expected to halve due to better compliance with the speed limit and the rollout of advisory ISA technologies. Serious incidents will reduce substantially following increased automation of vehicles and enhanced warning systems. The fatality rate is expected to remain as a zero value although this does not remove the chance of a potentially very serious incident should one of the technologies (i.e. platooning) fail as the systems are not expected to be infallible.

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

Table 7.5: - Projected Safety Record (Source: Kolosz et al, 2013b)

7.4 Cost-Benefit Analysis

A Cost-benefit analysis was performed on ATM, ISA and AHS. The areas focused on in the study were the data center energy emissions, the embedded emissions of the road-side infrastructure, vehicle tailpipe emissions, additional hardware required by the vehicles if applicable and safety. These represent key assets owned by the main 'stakeholder' elements of a typical ITS project. As discussed earlier in the thesis (Chapter 4, section 4.3.1), dual discounting was applied which aims to provide a separate discount rate for environmental elements. A different appraisal period was applied for each technology based upon their expected lifespan

7.4.1 Data collection

The first task was to identify the mitigation costs of climate change. Traded and non-traded mitigation costs are used to express in tonnes CO_2 eqv. the elements that drive the appraisal process. The value placed on carbon emissions in the short-term depends on the sector in which they are emitted. The 'traded sector' values are used for all relevant emissions from those sectors that are included within the EU Emissions Trading Scheme (EU ETS). These carbon values are based on expected EU ETS allowance prices because such prices reflect the abatement costs in those sectors. Where it is possible to identify the impact of the proposal on emissions overseas or on emissions that occur outside the target framework (e.g. imported steel produced in Germany for example), the change in emissions overseas should be valued at the Traded Price of Carbon (DECC, 2012). Only the vehicle emissions were assessed using non-traded carbon values. The traded and non-traded carbon values differ initially but converge towards 2030, the date from which they are assumed to become equal and subsequently follow the same trajectory. The convergence of the traded and non-traded values is based on the assumption that there will be a functioning global carbon market by 2030 (DfT, 2012a). According to the DfT's transport appraisal guidance (2012a), the non-traded price[1] of greenhouse gas mitigation relative to 2010 was £53.58 (€62.68) per tonne of CO_2 eqv. while the traded cost was £12.41 (€14.51). The costs were regressed to 2005 allowing the modelling data to be taken into account for analysis. The EU ETS was introduced in 2005, however as the government only recently published new guidance on carbon valuation (including switching from carbon to CO_2 eqv.) in 2008, the figures from 2010 were used for this period. These figures do not include the recent introduction of a carbon price floor introduced in April 2013, which affected only the power sector (HMT, 2011). Accident prevention for highways in 2010 was £2,052,377 for fatal, £246,217 for serious and 30,231 for minor accidents (DfT, 2012b). For the purposes of appraisal it was necessary to form a view on how these costs would vary over future years. Most elements in terms of values of prevention in road accidents and casualties are proportional to average income, so they were assumed to increase in line with real GDP per head with an elasticity of unity (DfT, 2012c). From 2061 onward, the GDP values are fixed, meaning the cost of prevention remains equal to the previous year.

Year	Traded Mitigation Costs (£/tonne CO_2eqv.)			Non-Traded Mitigation Costs (£/tonne CO_2eqv.)			Accident Prevention (£/per person)		
	Low	Central	High	Low	Central	High	Fatal	Serious	Minor
2005	12.41	12.41	12.41	26.79	53.58	80.37	2,037,201	244,396	30,007
2010	12.41	12.41	12.41	26.79	53.58	80.37	2,052,377	246,217	30,231
2015	11.24	18.46	22.99	28.86	57.72	86.59	2,169,210	260,233	31,952
2020	18.72	27.89	34.68	31.09	62.18	93.28	2,380,176	285,542	35,059
2025	27.50	50.22	71.75	33.68	67.37	101.05	2,604,032	312,397	38,357
2030	36.27	72.55	108.82	36.27	72.55	108.82	2,853,983	342,383	42,038
2035	53.12	106.23	159.35	53.12	106.23	159.35	3,155,346	378,537	46,477
2040	69.96	139.92	209.87	69.96	139.92	209.87	3,503,267	420,276	51,602
2045	86.80	173.60	260.40	86.80	173.60	260.40	3,914,372	469,595	57,658
2050	103.64	207.28	310.92	103.64	207.28	310.92	4,354,506	522,396	64,141

Table 7.6: - Climate change mitigation values and accident prevention, expressed in 2010 prices (Source: DfT, 2012a; DfT 2012b)

[1] NOTE: At the time of reporting, £1 = €1.17, $1 = 0.64p.

The valuation of fuel savings from the ITS schemes also had to be taken in to account. In 2011 the resource cost of petrol was 51.95p/litre while diesel was 56.11p/litre. Future projections up to 2030 carried out by DfT (2012c) were originally based upon the Gross Domestic Product (GDP) deflators relative to 2010 prices and reflects the prices of all domestically produced goods and services in the economy. Hence, the GDP deflator also includes the prices of investment goods, government services and exports, and subtracts the price of UK imports.

The disadvantage of using this index is its insensitivity to predicted changes in crude oil prices, therefore the resource cost of fuel for petrol and diesel in this study was forecasted based upon the projected price ratio of crude oil per barrel up to 2030 (DECC, 2013). The starting price was based on the futures curve for 2013. The range around this price was based on the average (absolute) percentage error from using the futures curve to predict prices for the coming 12 months between January 2000 and January 2013. However due to the forecast only being carried out up to 2030, the UK retail price index (0.195% per year) is used to project the resource cost of fuel post 2030.

Upper and lower bounds were performed based upon the three DECC scenarios (DECC, 2013). The low scenario 2030 price is based on an assessment of the long-run marginal cost curve for oil, based primarily on the international energy agency's estimates, choosing a level at which the majority of sources of unconventional oil will remain economic. To derive the 2030 high scenario price, the DECC supply and demand model was adjusted to incorporate zero global supply growth in oil over the period to 2030 and the results are then sense-checked against external high oil price scenario estimates. Having established an estimate for the 2030 price, the 2013 and 2030 prices were linked with a constant compound annual growth rate. Table 7.7 illustrates the UK resource cost of fuel for petrol and diesel. Electricity prices were backdated to 2005 using the appropriate RPI price index and from 2030 they were projected based upon the change in traded mitigation costs for climate change as assumed by DfT (2012c). As the consumption of the ATM infrastructure and data center are powered via a single phase low voltage supply, the prices are based on domestic valuation indexes.

Year	Resource Cost for Petrol (pence/l)			Resource cost for Diesel (pence/l)			Resource cost of domestic electricity supply (pence/kWh)
	Low	Central	High	Low	Central	High	
2005	30.76	30.76	30.76	34.41	34.41	34.41	11.72
2010	42.57	42.57	42.57	44.31	44.31	44.31	12.35
2015	43.50	53.06	62.00	48.38	59.01	68.96	16.20
2020	40.58	56.35	70.66	45.14	62.68	78.59	17.96
2025	37.85	59.83	80.55	42.10	66.55	89.59	19.74
2030	35.31	63.55	91.80	39.27	70.69	102.11	20.60
2035	34.96	64.17	92.69	38.89	71.38	103.10	20.29
2040	34.62	64.79	93.59	38.51	72.07	104.10	19.22
2045	34.27	65.41	94.48	38.12	72.76	105.09	19.22
2050	33.93	66.03	95.38	37.74	73.45	106.09	19.17

Table 7.7: - Resource cost of fuel expressed in 2013 prices and derived from oil price projections (Source: DfT, 2012c; DECC, 2013)

The CBA was performed based upon a revised dual discounting methodology. The typical discount rates from the governments 'green book' were used to apply discount on socio-economic values (i.e. 3.5% for the first 30 years and 3.0% for the remaining 30). However, the environmental benefits were given a lower discount rate of 1.5% for the first 30 years and then 1.0% thereafter (Kula and Evans, 2011). The reasoning behind this approach is due to the contradictory nature of applying a discount rate designed to increase socio-economic prosperity with a potential negative impact towards the natural eco-system and then also applying the same rate to environmental benefits.

> *"A common discount rate for both natural capital and manmade capital cannot be assumed as natural capital is finite and limited whereas man made capital is not limited. Hence there should be dual discount rates." (Kula and Evans, 2011)*

The next three sections illustrate the valuation of the three technologies under investigation.

7.4.2 Appraisal of Active Traffic Management

The valuation of ATM was carried out from 2005 to 2065 using its expected 25 year lifespan. The first task was to estimate the mitigation costs of climate change by assigning the traded and non-traded emissions price values with the GHG emissions of the scheme. All GHG's except the vehicle emissions are assigned traded mitigation values for climate change. The historical baseline is set at 2005, despite recommendations by the DfT to introduce the starting year no further than 5 years from the present. This is due to ATM already being implemented and was selected so that the embedded emissions could be taken into account. Maintenance costs and the eventual removal process have been extrapolated to

2065 but traffic data and the CO_2eqv/kWh of the energy grid and data center are fixed up to 2050 due to a lack of data. Figure 7.8 illustrates the mitigation costs for the embedded (Including operational) emissions in the scheme. Figure 7.9 illustrates the cost of the mitigation for the data center.

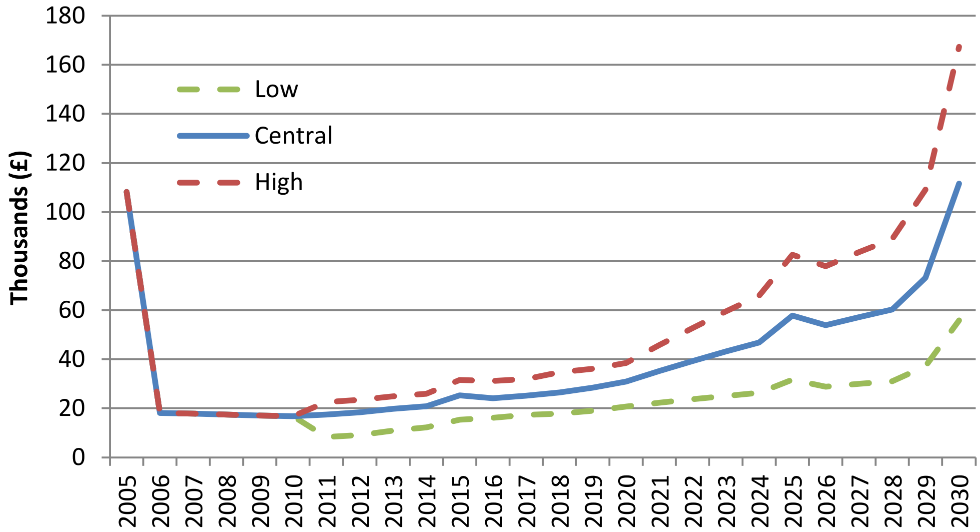


Figure 7.8: - ATM embedded emissions mitigation costs

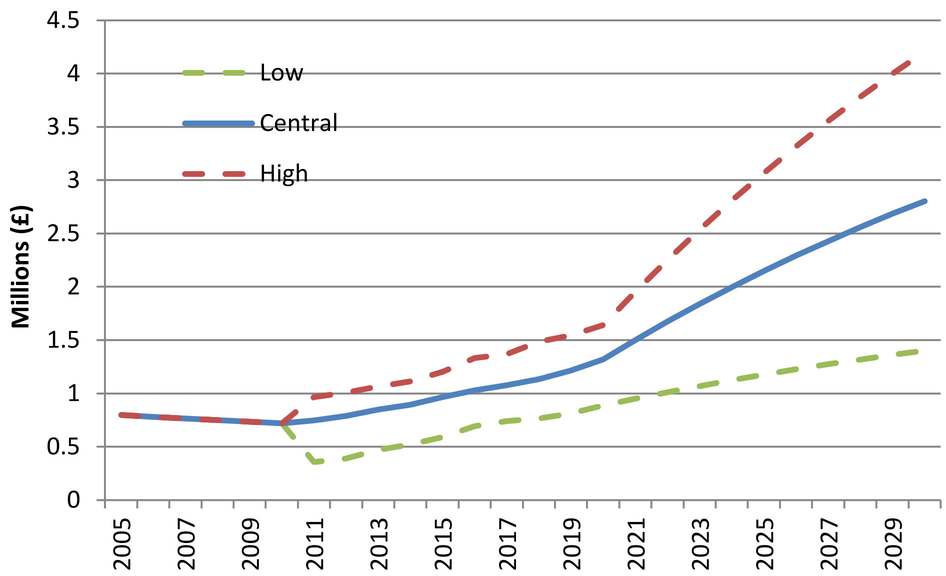


Figure 7.9: - ATM data center emissions mitigation costs

The savings in terms of vehicle emissions were valued based on the non-traded mitigation costs. The expected technological improvement in engine efficiency and GHG capture is projected up until 2050. The values are then fixed up to 2065.

Figure 7.10 illustrates these savings. Accident prevention benefits were calculated yearly based upon the difference between the average accident trends before (1998-2003) and after (2006-2009) where the six month trial assessment (no temporary shoulder running) was combined with the three year review (Self, 2011).

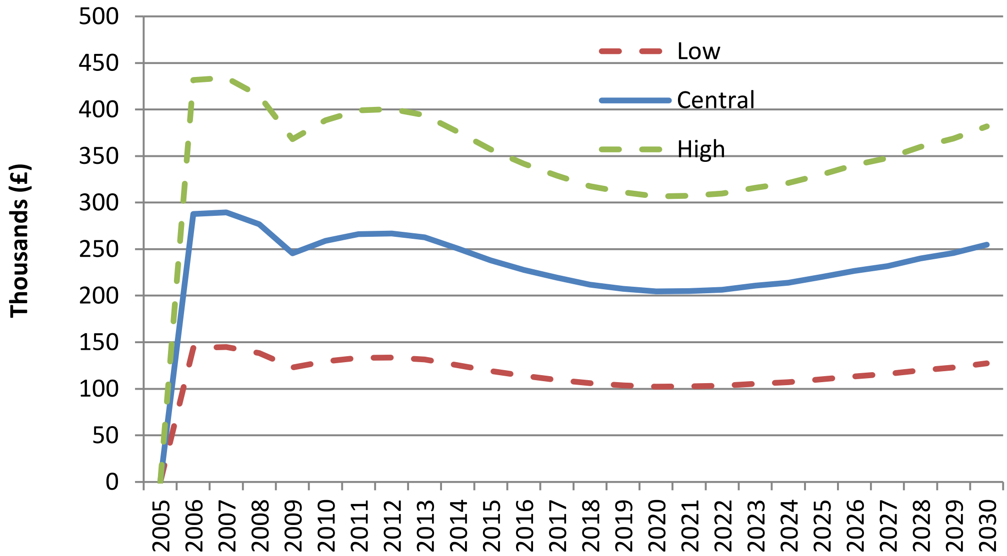


Figure 7.10: - ATM vehicle emissions mitigation savings

Figure 7.11 illustrates the total savings of the ATM scheme on the M42 categorised into Fatal, Serious and minor accidents per person.

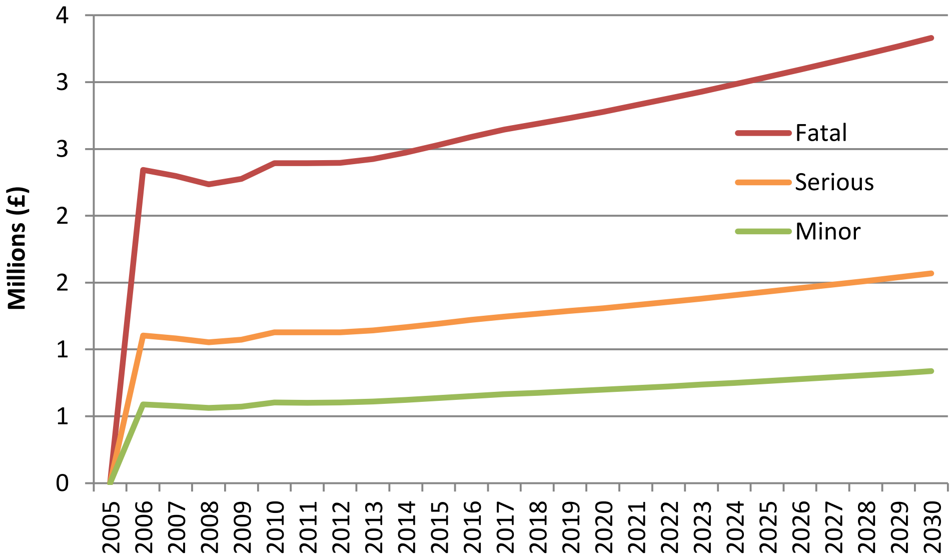


Figure 7.11: - ATM Accident prevention savings

The reduction in fuel consumption in terms of petrol is illustrated in Figure 7.12. Towards 2050, the saving of fuel diminishes. This is due to several assumptions. Firstly, the expected market share of petrol is reduced due to better fuel efficiency of diesel (see Figure 7.3). Secondly, the technological maturity of electric vehicles, bio-diesel and other alternative fuels will reduce this market share even further (Shafiei et al, 2012). The savings of diesel in Figure 7.13 are expected to increase due to the rise in market share although the reduction of 4% fuel consumption remains constant.

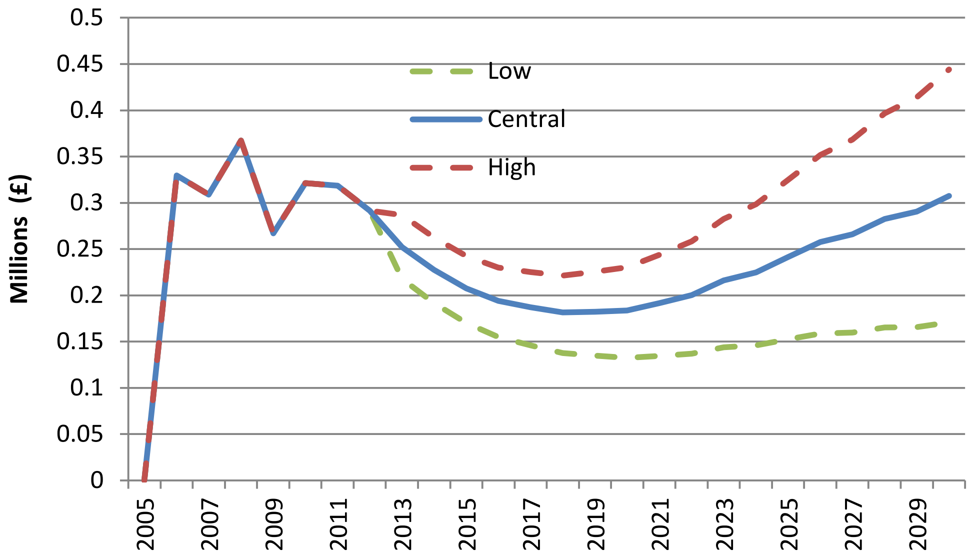


Figure 7.12: - ATM Petrol Fuel Consumption Savings

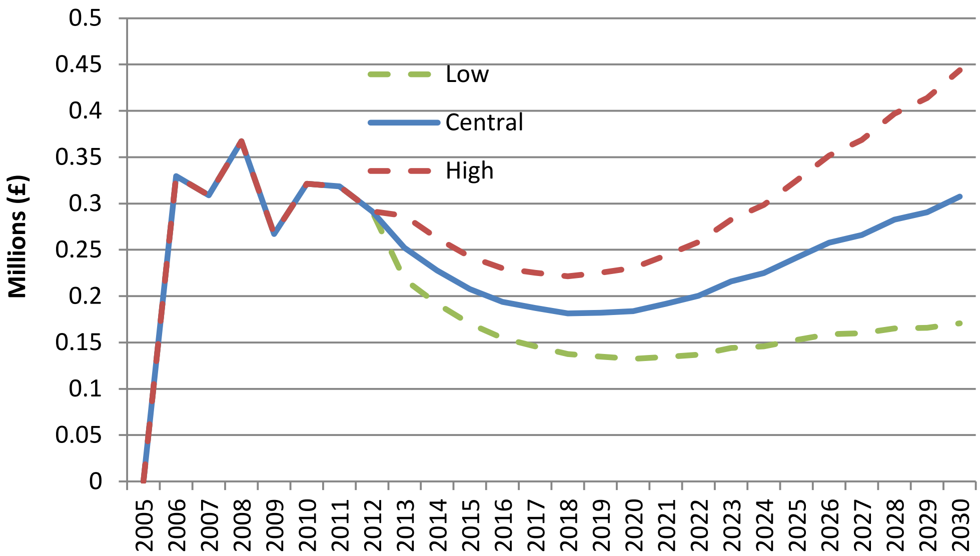


Figure 7.13: - ATM Diesel Fuel Consumption Savings

The results of the CBA for ATM is illustrated in Table 7.8. The initial capital cost in 2005 represents the procurement of materials, production costs, installation and staff wages. As discussed earlier, the environmental costs and benefits were discounted separately at a rate of 1.5% in the first 30 years and 1% thereafter. The results indicate that the project provides strong benefits as indicated through cost

Year	Total Discounted costs (£)	Socio-Economic Benefits (£)	Environmental Benefits (£)	Discounted Net benefits (£)	Net Present Value (£)	Benefit-Cost Ratio
2005	96,508,174	0	0	0	-96,508,174	0.00
2006	770,551	4,407,997	287,879	4,537,278	3,766,728	5.89
2007	755,093	4,308,641	289,381	4,442,878	3,687,786	5.88
2008	739,946	4,276,276	276,621	4,399,078	3,659,132	5.95
2009	725,105	4,222,512	245,429	4,316,471	3,591,366	5.95
2010	710,563	4,495,427	258,844	4,593,048	3,882,485	6.46
2011	738,407	4,511,839	266,111	4,616,043	3,877,636	6.25
2012	779,134	4,495,655	266,835	4,601,140	3,822,006	5.91
2013	837,318	4,506,165	262,573	4,607,084	3,769,766	5.50
2014	881,767	4,561,921	250,715	4,649,209	3,767,442	5.27
2015	957,752	4,637,290	238,101	4,709,514	3,751,762	4.92
2016	1,016,576	4,722,897	227,794	4,781,973	3,765,397	4.70
2017	1,063,750	4,808,932	219,233	4,856,564	3,792,813	4.57
2018	1,118,835	4,875,624	211,835	4,913,634	3,794,799	4.39
2019	1,198,962	4,950,798	207,349	4,981,759	3,782,797	4.16
2020	1,303,938	5,028,610	204,451	5,053,993	3,750,055	3.88
2021	1,482,544	5,124,453	204,862	5,146,887	3,664,342	3.47
2022	1,653,006	5,218,692	206,427	5,239,368	3,586,362	3.17
2023	1,816,466	5,322,332	210,685	5,343,575	3,527,109	2.94
2024	1,972,279	5,427,096	214,042	5,447,979	3,475,700	2.76
2025	2,128,677	5,536,658	220,069	5,559,644	3,430,967	2.61
2026	2,263,987	5,648,989	226,773	5,674,647	3,410,659	2.51
2027	2,399,470	5,756,145	231,909	5,783,110	3,383,640	2.41
2028	2,528,991	5,874,243	239,839	5,904,886	3,375,895	2.33
2029	2,661,639	5,987,096	245,975	6,019,833	3,358,194	2.26
2030	2,813,299	6,111,085	254,664	6,148,040	3,378,710	2.22
TOTAL	**131,826,229**	**124,817,373**	**5,968,396**	**126,327,635**	**-5,454,625**	**2.22**

Table 7.8: - Cost Benefit Results for ATM

benefit ratio metrics. Although these benefits manifest strongly at the beginning of the scheme, their effectiveness is reduced due to rising costs in terms of energy prices and climate change mitigation fees. The Net Present Value (NPV) for ATM indicates that the scheme produces a negative outcome and therefore does not recuperate its initial starting capital by the end of its lifecycle. This may be avoided on future schemes through improving the energy efficiency of the data center as discussed in Chapter 6 and also through reducing energy consumption of the road-side infrastructure through renewable energy technologies such as solar panels and small scale windmills this would require a switch to a medium voltage network (Holt and Pengelly, 2008). The BCR has a factor of 2.22 which is a positive outcome.

7.4.3 Appraisal of Intelligent Speed Adaptation

The valuation of Intelligent Speed Adaptation was carried out between 2010 and 2050 using a 40 year appraisal period. As with the appraisal of ATM, the savings of vehicle emissions are combined with climate change mitigation prices. As ISA is only expected to provide benefits to cars and LGV (HGV's feature speed limiters up to 60 mph), only the savings of emissions from those vehicles were taken into account. The historical baseline is set at 2010. As discussed in section 7.3, it was assumed that the ISA technology operates independently from the road-side side infrastructure where vehicles communicate via satellites to identify location with on board digital mapping software was preferred. Data center emissions were therefore not taken into account when assessing this technology. Figure 7.14 illustrates the vehicle emissions mitigation savings of ISA. Note that there is a spike in savings which is due to a combination of two factors. The sudden rise in non-traded mitigation values and the mandatory ISA technology becoming active which gives an increased emissions saving from 3.4% to 5.8%. The sudden fall is illustrated due to the estimated reduction in conventional vehicle market share and the rise of alternative fuels.

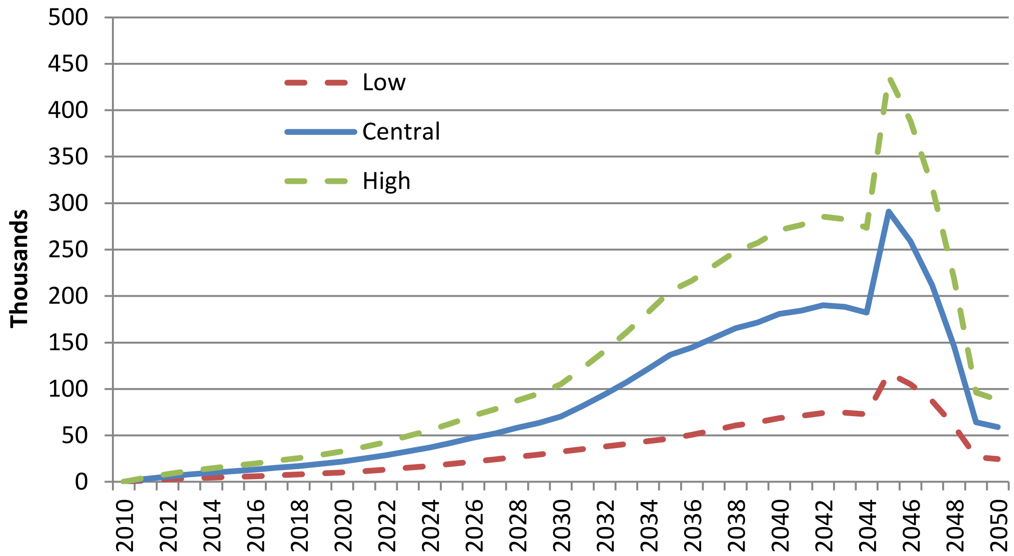


Figure 7.14: - ISA vehicle emissions mitigation savings

As with ATM, accident prevention was calculated based upon the initial safety assessment conducted between 1998-2003, although the average annual accident ratios were divided based upon the expected ratio of accident prevention for the three ISA technologies. The percentile was based upon the expected market share as illustrated in table 7.9. Figure 7.15 illustrates the predicted accident savings.

ISA penetration	Safety prevention on motorway		
	Advisory (%)	Voluntary(%)	Mandatory (%)
20	0.9	1.8	3.6
40	1.8	3.6	7.3
60	2.8	5.4	10.9
80	3.7	7.2	14.5
100	4.6	9.0	18.1

Table 7.9: - ISA safety prevention per technology (Source: Lai and Carsten, 2012)

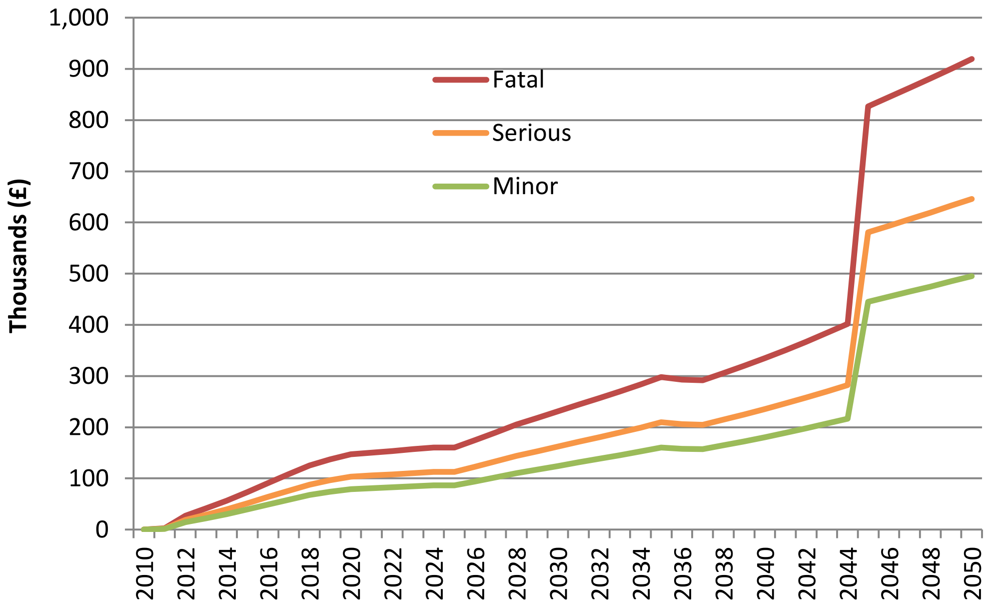


Figure 7.15: - ISA accident prevention savings

Figures 7.16 and 7.17 illustrates the expected savings of petrol and diesel fuel consumption due to the combination of Advisory, Voluntary and Mandatory ISA technologies. Once again, there is a spike due to the introduction of mandatory ISA technologies although the expected savings diminish due to the reduced market share in petrol, although diesel is expected to retain a high market share.

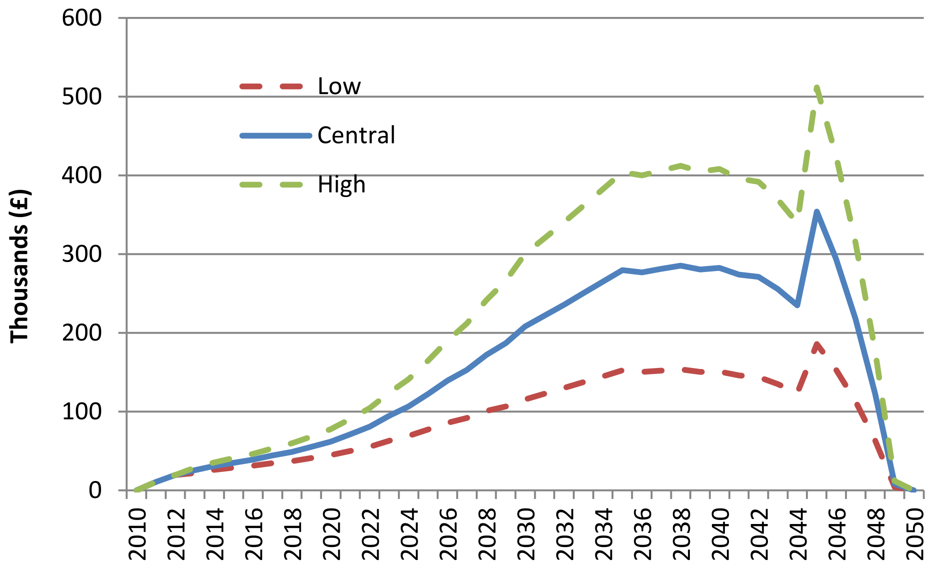


Figure 7.16: - ISA Petrol Fuel Consumption Savings

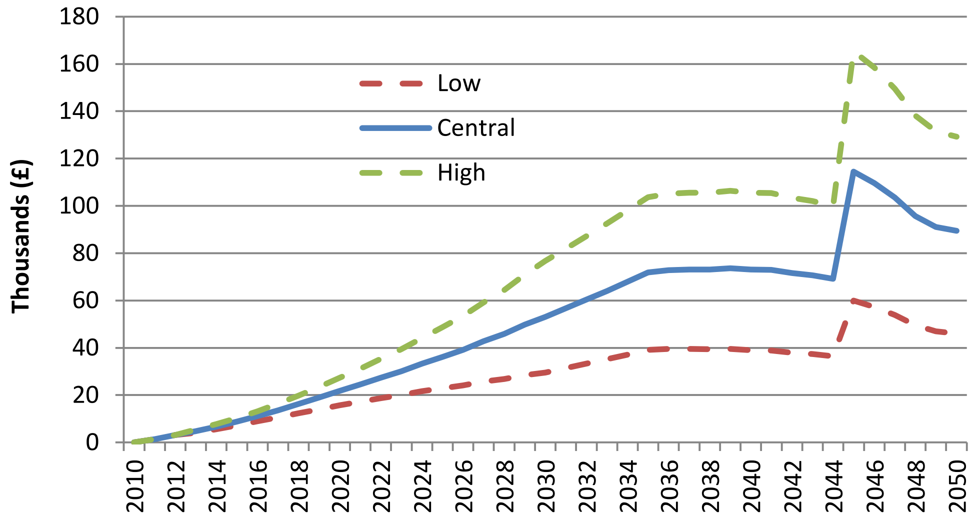


Figure 7.17: Diesel Fuel Consumption Savings

The results of the CBA applied to ISA is illustrated in Table 7.9. Overall there is a negative cost benefit ratio and net present value indicating initially that ISA on the M42 may be infeasible due to the high level of hardware costs. However, as noted by Lai and Carsten (2012) this may not be the case when assessing the technology from a national perspective as shown by a positive BCR in 2025 and the technology may still recuperate its benefit once the hardware becomes standardised and the system matures. This does however indicate that in the first 45 years the majority of the savings is outweighed by the cost to retrofit vehicles before 2045 (the mandatory date) which is considerably more expensive than to install during the vehicle manufacturing process as indicated in table 7.3.

Year	Total Discounted Costs (£)	Socio-Economic Benefits (£)	Environmental Benefits (£)	Discounted Net benefits (£)	Net Present Value (£)	Cost-Benefit Ratio
2010	100,060	0	0	0	-100,060	0.00
2015	1,220,448.53	208,285	11,489	212,312	-1,008,137	0.17
2020	11,994,213.71	413,629	21,933	420,756	-11,573,458	0.04
2025	36,742,807.32	517,760	42,035	541,042	-36,201,765	0.01
2030	54,399,856.22	778,677	70,171	820,542	-53,579,314	0.02
2035	76,483,151.68	1,020,009	136,941	1,119,195	-75,363,956	0.01
2040	86,506,128.04	1,106,835	180,687	1,073,630	-85,432,498	0.01
2045	6,048,090.70	2,321,417	291,074	2,251,775	-3,796,316	0.37
2050	6,373,507.03	2,150,448	58,862	2,085,934	-4,287,573	0.33
TOTAL	1,561,912,156.57	35,919,631	3,716,177	34,842,042	-1,527,070,114	0.33

Table 7.9: - Cost Benefit Results for ISA

Alternatively, by introducing the hardware during the vehicle manufacturing process and restricting the cost in terms of retrofitted vehicles, a positive BCR and net present value could be achieved.

7.4.4 Appraisal of Automated Highway Systems

The valuation of AHS was carried out between 2030-2050. The main assumptions are that AHS operates on one lane and only cars will be equipped with the technology. This is due to the platoon and capacity performance being reduced when incorporating a mixture of different vehicles sizes which may affect the aerodynamic flow of the platoon (Psaraki et al, 2012). In addition, as some road-side infrastructure is still required, the energy costs of the data center controlling the equipment is taken into account and this is illustrated in Figure 7.18. It is expected that vehicular ad-hoc networks will also be in operation, although there is insufficient data to accurately determine their cost in terms of manufacturing the components and also their energy consumption. The installation costs of installing the in-vehicle equipment necessary for platooning has been included.

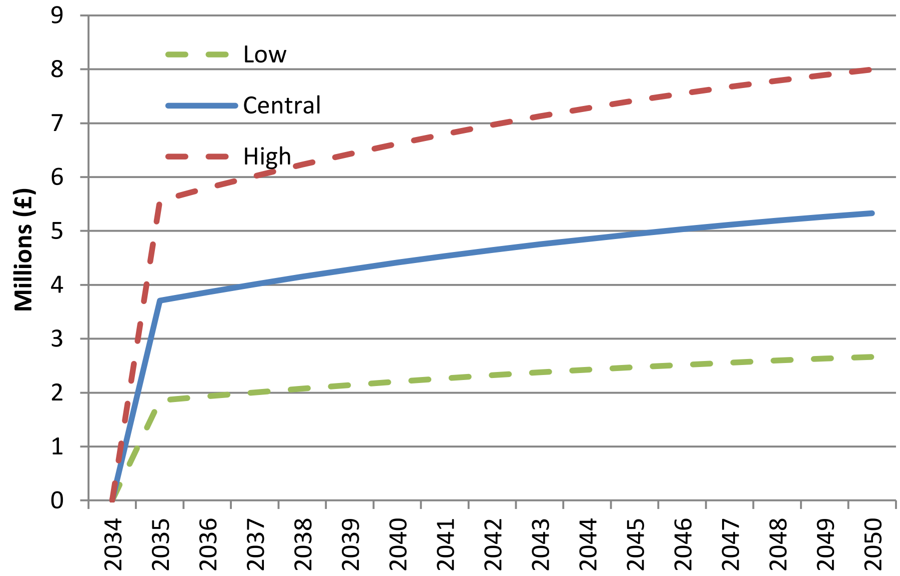


Figure 7.18: - AHS data center mitigation costs

AHS is expected to reduce emissions by around 20% and this level of reduction was combined with the non-traded carbon mitigation values to determine its vehicle emission savings. The results are displayed in Figure 7.18

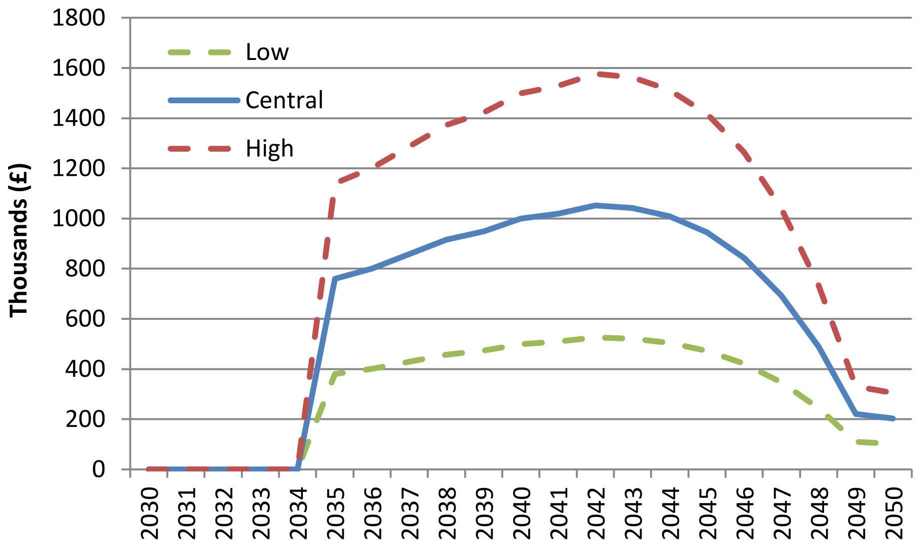


Figure 7.18: - AHS vehicle emission mitigation savings

Accident prevention for the AHS system is expected to be very high considering that the system is fully automated. As human error is eliminated the automated system keeps the platoons synchronised, although the system is not expected to be infallible. If an accident does occur it could potentially affect the entire platoon and thus increase the scale of the accident more than operating without platooning, although recent research indicates platooning could adhere to the legal safety (distance, perception etc) of the driver to reduce accidents (Vaa et al, 2007; Vanholme et al, 2013). The system is expected to be resilient to faults, whether mechanical or preventing external anomalies such as debris from reducing the performance of AHS.

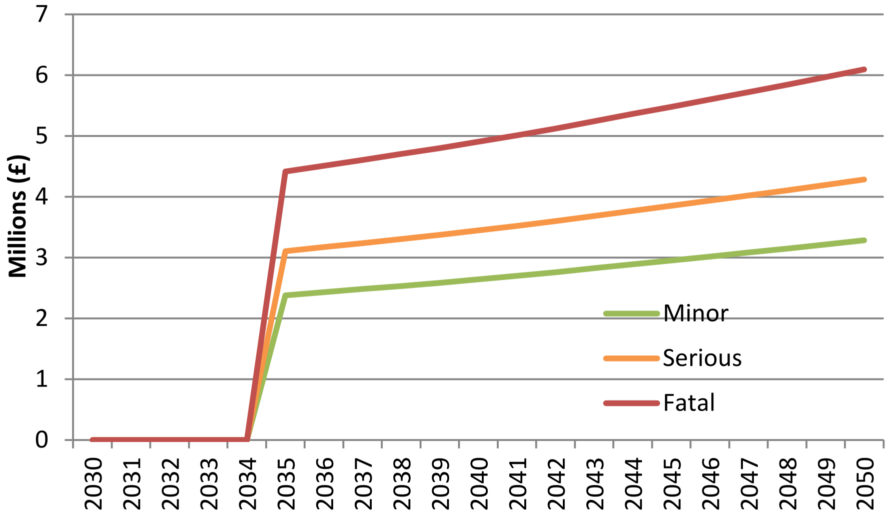


Figure 7.19: - AHS accident prevention savings

The expected savings of fuel consumption can be viewed in Figures 7.20 and 7.21. The savings of fuel is quite substantial, though only cars will expect to have reduced fuel consumption for the purposes of this study.

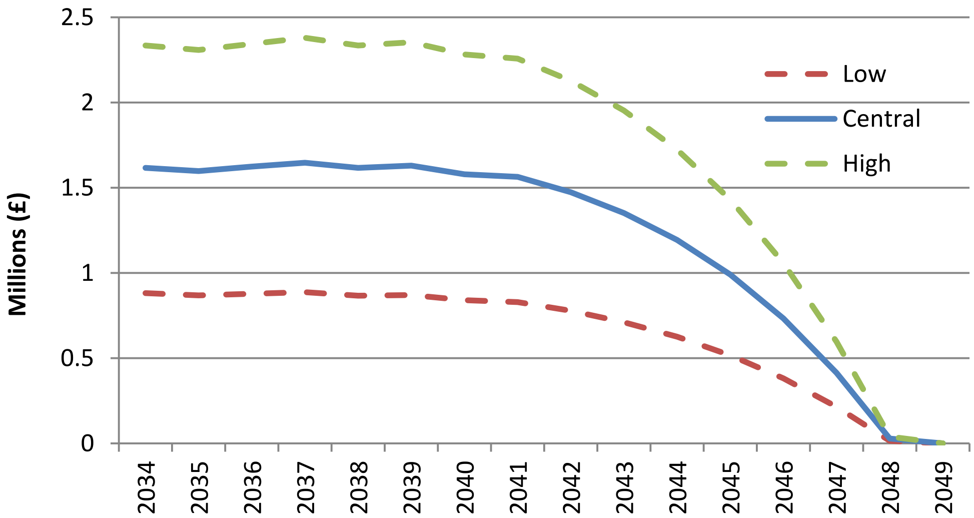


Figure 7.20: - AHS Petrol Fuel Consumption savings

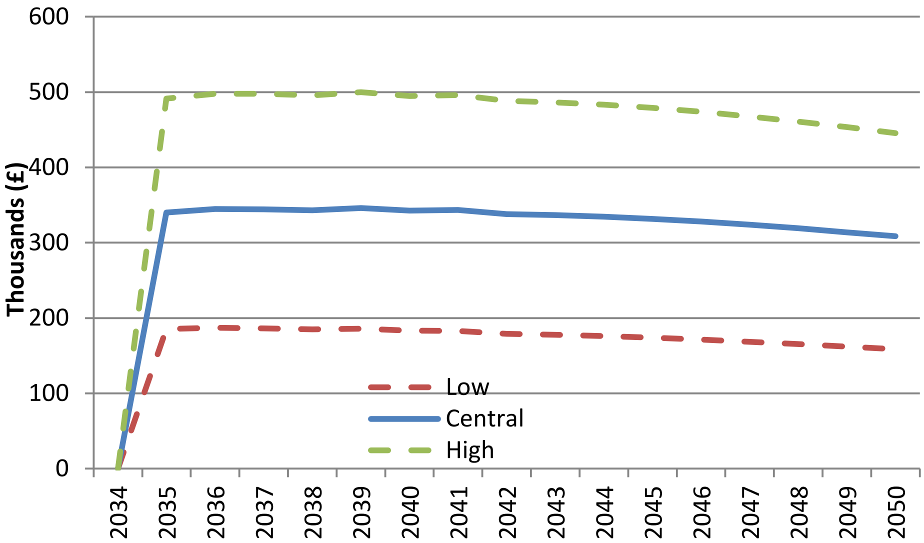


Figure 7.21: - AHS Diesel Fuel Consumption savings

The results of the CBA for AHS is illustrated in table 7.10. Note that the year of expected AHS operation has been regressed to 2032 in order to simulate the cost of installing the equipment on selected vehicles in preparation for the eventual deployment in 2035. Upon initially viewing the results, the cost benefit ratio and net present value indicate a negative return upon investment. This is due to the installation costs of installing the automation equipment on the vehicle as illustrated in Figure 7.7b. In reality, the vehicle may be sold at a higher price in order to offset these costs. If the costs for installation are negated however, a positive BCR and net present value is attained.

Year	Total Discounted Costs (£)	Socio-Economic Benefits (£)	Environmental Benefits (£)	Discounted Net benefits (£)	Net Present Value (£)	Benefit-Cost Ratio
2032	23,340,349	0	0	0	-24,186,890	0.00
2033	35,441,767	0	0	0	-36,727,220	0.00
2034	35,873,269	**0**	**0**	0	-37,174,372	0.00
2035	15,698,641	5,060,157	759,948	5,631,599	-10,067,041	0.36
2036	128,668,968	5,113,698	800,802	5,723,508	-122,945,459	0.04
2037	129,969,605	5,204,317	857,951	5,867,247	-124,102,358	0.05
2038	131,627,535	5,294,070	915,062	6,010,114	-125,617,421	0.05
2039	133,279,577	5,335,228	948,195	6,082,468	-127,197,109	0.05
2040	134,925,710	5,418,157	999,368	6,212,899	-128,712,811	0.05
2041	136,565,870	5,444,162	1,018,758	6,257,092	-130,308,777	0.05
2042	138,200,784	5,500,535	1,051,781	6,344,021	-131,856,763	0.05
2043	139,830,433	5,491,848	1,041,844	6,325,850	-133,504,584	0.05
2044	141,454,691	5,454,006	1,008,348	6,256,338	-135,198,353	0.04
2045	277,304,954	5,376,100	944,673	6,118,439	-271,186,515	0.02
2046	281,512,477	5,253,689	842,754	5,899,923	-275,612,554	0.02
2047	284,652,689	5,076,032	693,855	5,581,818	-279,070,871	0.02
2048	287,789,593	4,837,401	488,369	5,149,136	-282,640,457	0.02
2049	290,923,309	4,535,103	220,118	4,593,191	-286,330,118	0.02
2050	294,053,696	4,592,152	202,972	4,631,354	-289,422,342	0.02
TOTAL	**3,041,113,917**	**82,986,655**	**12,794,798**	**92,684,999**	**-2,951,862,015**	**0.02**

Table 7.10: - Cost Benefit Results for AHS

7.5 Performance Indexing

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

7.5.1 Estimating Performance from Future targets

A set of interim targets based upon regional and national forecasting scenarios were added to cover key milestones which are 2020, 2030 and 2050 time points.

Table 7.11 illustrates the distance to target method which was used in order to develop a set of weights based on how far each criterion is from its desired target. It is important to note that because the infrastructure is expected to undergo substantive changes, external systems such as a centralised data center may only operate for a limited period of time. It has also been assumed that functions delivered by the traffic management services of ATM will be delivered by in-vehicle systems by 2030, therefore a DTT value of 1.0 (i.e. the maximum possible value) has been assumed and applied.

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

Table 7.11: - Distance To Target Weighting For M42 Junction 3a-7 (Source: Kolosz et al, 2013b)

7.5.2 Prioritising Key Performance Areas

Table 7.12 illustrates the weights for the data fusion using the global performance ranking (GPR), the DTT function and the analytical hierarchy process based upon the index-normalised performance rankings in table 2. In this study, note that BPA's are only given up to 2030 on select criteria. This is due to the assumption that the ATM scheme is withdrawn from service and the fact it is difficult to acquire data for the particular criteria for the future technologies. In this instance, it is assumed that the BPA's for 2050 are set at 'very high' (1.0) to reflect the positive changeover in technology from fixed infrastructure to a dynamic ad-hoc network (vehicular network).

Performance Criteria	**Intelligent Transport Sustainability Index (2012-2050)**					
***BPA's given up to 2030 only**	***GPR***	***BPA's 2012***	***BPA's 2050***	***DTT weighting***	***AHP***	***ITSI Value***
Roadside infrastructure emissions (C_1)*	0.5 X 0.7 X 0.9 X	L = 0.02521 M = 0.94736 H = 0.03157	L = 0.03448 M = 0.93103 H = 0.03448	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.042126 2030 = 0.042000
Road User Emissions (C_2)	0.5 X 0.7 X 0.9 X 1.0 X	L= 0.01639 M= 0.36885 H= 0.61475 VH=0	L=0.02631 M=0.96710 H=0.02970 VH=0.97029	X 0.9 (2012) X 0.9 (2050)	X 0.100	2012 = 0.073770 2050 = 0.089732
GWP Data Center offset (C_3)*	0.5 X 0.7 X 0.9 X 1.0 X	L=0.62790 M= 0.34883 H=0.02325 VH=0	L= 0.00042 M=0.00507 H=0.005074 VH=0.99450	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.034744 2030 = 0.099936
GWP per IT resource (C_4)*	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L = 0.02321 M = 0.97485 H = 0.00193	VL = 0.00394 L = 0.99408 M = 0.00197 H = 0	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.041744 2030 = 0.004996
Energy used per resource (C_5)*	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L= 0 M= 0.65217 H = 0.34782	VL = 0.90909 L= 0.09090 M = 0 H= 0.27778	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.046173 2030 = 0.009545
Annual DCIE/PUE for data center (C_6)*	0.3 X 0.5 X 0.7 X 0.9 X	VL = 0 L = 0.96991 M = 0.02850 H = 0.00158	VL =0.00458 L = 0.99082 M = 0.00458 H = 0	X 0.3 (2012) X 1.0 (2050)	X 0.100	2012 = 0.015190 2030 = 0.030000
Roadside Energy Consumption (C_7)*	0.5 X 0.7 X 0.9 X	L = 0.52941 M = 0.47058 H = 0	L = 0.17391 M = 0.81521 H = 0.01086	X 0.6 (2012) X 1.0 (2050)	X 0.100	2012 = 0.047647 2030 = 0.020021
Scheme Compliance (C_8)	0.7 X 0.9 X 1.0 X	M = 0.45454 H = 0.54545 VH = 0	M = 0 H = 0 VH = 1	X 0.9 (2012) X 1.0 (2050)	X 0.100	2012 = 0.072818 2050 = 0.100000
Safety (C_9)	0.9 X 1.0 X	H= 0.00307 VH =0.99692	H = 0.02000 VH =0.98000	X 1.0 (2012) X 1.0 (2050)	X 0.100	2012 = 0.099969 2050 = 0.098000
Scheme Cost (C_{10})	0.7 X 0.9 X 1.0 X	M= 0.00443 H=0.99334 VH=0.00221	M = 0 H=0 VH=1.00000	X 0.9 (2012) X 1.0 (2050)	X 0.100	2012 = 0.080940 2050 = 0.100000

Table 7.12: - Calculation of Intelligent Transport Sustainability Index (Source: Kolosz et al, 2013b)

Based upon the ITSI performance results in table 7.12, it is possible to produce a 'unified' analysis to reflect which areas of the ITS scheme are performing acceptably and which areas can potentially be improved. Table 7.13 illustrates the priority distribution. In 2020, from strongest (10) to weakest (1), the highest performing criterion (based upon the ITSI performance value) is 'Safety'. This is due to both the future target being met and also the subjective performance grade being rated as 'very high'. It is conjectured that this reflects an increased compliance with the speed limit (also highly rated). The lowest performing criterion is 'roadside energy consumption'. This is due to increasingly stringent targets being set for energy conservation. The assumption is made (for the purposes of the case study) that the procurement of new energy efficient systems is too costly for the road network operator, hence there is no reduction in energy usage. In this scenario there are no carbon reduction strategies in place, despite ICT having a major influence on the emissions and energy of the Active Traffic Management scheme. For 2030 this is reflected by falling levels of performance due to the increasing targets and reflecting no change concerning the use of carbon reduction strategies.With the correct knowledge and training, the energy efficiency of the data center may be improved, for example by following the guidelines in the EU Code of Conduct for Data Center Energy Efficiency. By 2050 however, the architecture of the system is expected to change removing the roadside infrastructure and centralized data center. This would have a direct impact on energy, embedded emissions and the cost of the scheme (the worst performer in 2050). Following removal of these systems, these criteria are not applicable for the final priority distribution.

Performance Criteria	**Normalised Performance Levels and Priority Distributions**				
	Apparent Performance Grade (2012-2050)	***ITSI Performance Value***	***Priority (2020)***	***Priority (2030)***	***Priority (2050)***
Roadside infrastructure emissions (C_1)	Medium-Medium	2012=0.042126 2050=0.042000	6	6	N/A
Road User Emissions (C_2)	High-Medium	2012=0.073770 2050=0.089732	8	5	2
GWP Data Center offset (C_3)	Low-V.High	2012 =0.034744 2030 =0.099936	7	8	N/A
GWP per IT resource (C_4)	Medium-Low	2012 =0.041744 2030 =0.004996	3	1	N/A
Energy used per resource (C_5)	Medium-Low	2012 =0.046173 2030 =0.009545	4	2	N/A
Annual DCIE/PUE for data center (C_6)	Low-Low	2012 =0.015190 2030 =0.030000	2	4	N/A
Roadside Energy Consumption (C_7)	Low-Medium	2012 =0.047647 2030 =0.020021	1	3	N/A
Scheme Compliance (C_8)	High-V.High	2012 =0.072818 2050 =0.100000	9	9=	4
Safety (C_9)	V. High-V.High	2012 =0.099969 2050 =0.098000	10	7	3
Scheme Cost (C_{10})	High-Very High	2012 =0.080940 2050 =0.100000	5	9=	1
OVERALL PERFORMANCE	**Medium-V.High**	**2012=0.555124 2050=0.892613**	**Energy**	**Enviro.**	**Economic**

Table 7.13: - Priority Distribution of Performance (Source: Kolosz et al, 2013b)

7.6 Discussion and Summary

This chapter has illustrated the second part of the study which aimed to forecast future ITS technologies using the EnvFUSION method. A cost benefit analysis was performed on Active Traffic Management, Intelligent Speed Adaptation and the Automated Highway System indicating that under the revised focus (assessing the status of ITS as a system of systems) all schemes contribute positively to sustainability in terms of high environmental and socio-economic benefits. Despite the energy costs of the data center and mitigation costs of its embedded emissions, a high cost-benefit ratio of 7.28 is achieved, although the scheme becomes less effective later on its lifecycle due to rising costs of energy. The next chapter illustrates the final part of the study which aims to model the socio-technical variables of ITS performance within the context of sustainability so that inter-scheme comparisons can be performed.

"...Studies (of ITS evaluation) have given out some different perspectives and solutions in ITS projects assessment and can be used in different circumstances but with limitations. However, the problem is that neither of them is organized in a whole-to-part and top-down structure; instead, they mostly go in a bottom-up and part-to-whole way" (He et al, 2010).

Chapter 8 - Modelling ITS Socio-technical Parameters for Inter-Scheme Comparisons

This chapter introduces the final part of the study which is to explore the relationships between sustainability and the socio-technical performance of ITS systems. A strategic performance management framework is proposed resulting in an inter-scheme comparison matrix which would be able to take into account all areas of ITS performance using a dynamic socio-technical model.

8.1 Chapter Overview

In chapters 6 and 7, a case study was created in order to estimate the performance of current and future ITS on a stretch of congested highway. Using the EnvFUSION framework, an Intelligent Transport Sustainability Index (ITSI) was created which could assist in prioritising areas of performance within the ITS service. The performance of such systems however are still hard to quantify due to the complex ICT subsystems attached and the socio-technical relationships between them. Specifically, when comparing one scheme that is geographically (region or country) or physically different with a similar service, the data had to be measured objectively in order to determine how they will perform in future product (service) rollouts of transport technology. This involved analysing different aspects of performance which included measuring the complexity of information, how driver information is structured and where it is located, as well as identifying any significant safety critical factors such as response times and the reinforcement of policy for ITS standardisation. Internationally, road network operators require new performance indicators to be developed which need to differ from those aimed towards more conventional highways (Highways Agency, 2009a, b). The National Cooperative Highway Research Program in America have recently published a report on the development of performance measures for sustainable transport (Zietsman et al, 2011) and also proposed how ITS can be implemented into the current transport planning process (Bunch and Emerson, 2002).

In this chapter, it can be argued that what was needed was the consolidation of the various key performance areas of ITS in order to assist in quantifying the socio-technical performance of the ICT layer, the performance behaviour between schemes as well as mapping their behavioural effects.

8.2 Implementing a performance management framework for ITS

This section proposes a strategic performance management framework for sectoral ITS scheme comparison. The toolkit is based upon a ‘bottom-up’ hierarchy of ITS technological performance management with three distinct layers – a strategic layer, tactical layer and operational layer as follows.

At its top level, an inter-scheme comparison matrix has been proposed which aims to deliver a comparison between similar or schemes with alternative technologies. The tactical layer represents the various performance cornerstones necessary for managing ITS as defined by the overall scope of the research. The operational layer consists of the metrics, measures and environmental system analysis tools (ESAT) used to support the four performance areas. The research presented here focuses upon the strategic layers of the toolkit. Future work will be able to identify performance criteria for each of the performance areas in the form of a dynamic model with inter-dependent relationships.

In the tactical layer, the proposed performance areas represent the general cornerstones across four main areas of managing ITS within an inter-urban environment i.e. standardisation, data management, adaptability and EnvFUSION (a self-contained framework aimed at assessing the socio-economic and environmental of the physical road-side infrastructure and ICT data links), each comprising a technical performance index. The ITS performance management frameworks route to optimisation is expressed via standardisation protocols.

Finally, the strategic layer integrates all four performance areas and features a performance matrix designed to perform inter-scheme comparisons of ITS services within a national/sectoral region. Network operators will be able to develop their own criteria based upon their own requirements, vision and mission statement. Figure 8.1 illustrates the strategic performance management framework originally proposed in Kolosz et al (2012). As an example, the focus of the operational layer is tuned to the socio-economic and environmental assessment – EnvFUSION and other elements within the tactical layer would have their own operational tools, metrics and measures.

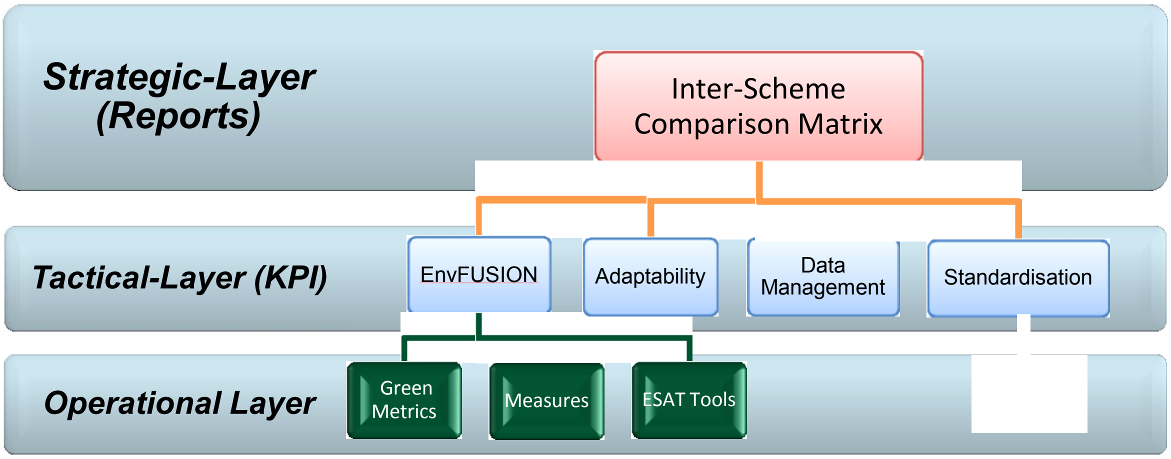


Figure 8.1: - ITS Strategic Performance Management Framework (Source: Kolosz et al, 2012)

The four key performance indicators (KPI) in the tactical layer represent not only the technical side of maintaining the performance via *continual service improvement*

(ITS is built from an IT/technical infrastructure therefore scientific measures must be implemented objectively) but also to reinforce the governance of existing and future transport planning based upon governmental policy (Department of Energy and Climate Change, 2009a).

8.3 Review of Performance Management for ITS (Overview)

In Chapter 2, socio-economic and environmental sustainability with regards to ITS were defined within a multi-disciplinary approach to tackling a wider problem area. The ability of transport and IT services to blend seamlessly into a continuous and optimal state under a low-carbon mode required analysis from different perspectives as well as varying levels of detail. To summarise these findings, the following factors may be taken into account that provide a holistic view on tackling ITS performance.

Some authors maintain that a future transport network (Valsera-Naranjo et al, 2009; Žilina, 2009; Vu et al, 2010) will consist of a variety of integrated wireless communications delivering seamless real-time data to the transport network. Transmitting this data becomes complex due to a wide variety of data types and transmission sources (Reijmers et al, 1995; Shladover, 2005; Tarte et al, 2010). In addition, these data sources need to be protected against malicious attacks (viruses, hackers etc) via maintaining its integrity (Raya and Hubaux, 2005).

Definitions of performance in ITS must take environmental issues into account in order to assist in the reduction of climate change. The 'low-carbon' infrastructure should be in place to negate the effects of carbon emissions and energy wastage from the road network (Commission for Integrated Transport, 2007; Brown et al, 2010). In addition, the task is made fundamentally complex due to sectoral targets of not only reducing transport but also applying pressure on providing a 'green' ICT energy consumption (Cabinet Office, 2009; Crooks et al, 2009; Ruth, 2009; Feng et al, 2010). Additional performance measures are needed to estimate the success of carbon and energy initiatives within ITS (Transport and ICT perspectives) in order to achieve the required goals for the future. Performance for ITS also requires a certain level of adaptability. For example, vehicular networks must be able to maintain a constant connection, defying environmental interference against natural landscapes (hills, mountains), weather systems, natural disasters and artificial data blockades such as tunnels (Spanos and Murray, 2004). In addition, a socio-technical perspective must indicate how future ubiquitous transparent (easily perceived) services will behave and perform in a way that allow users of the network reassurance of optimal safety, navigation and O-D (Origin-

Destination) planning (Tuominen and Ahlqvist, 2010; Vlassenroot et al, 2010). Indicators must be in place to define how transport services maintain user adoption.

A final note on performance definition was the ability to standardise and allow true network compatibility across the varying technologies both now and in the future. Network standards should be developed which are universally compatible with infrastructure, data types and transmissions (ITU-T, 2008; Highways Agency, 2010a; Tarte et al, 2010).

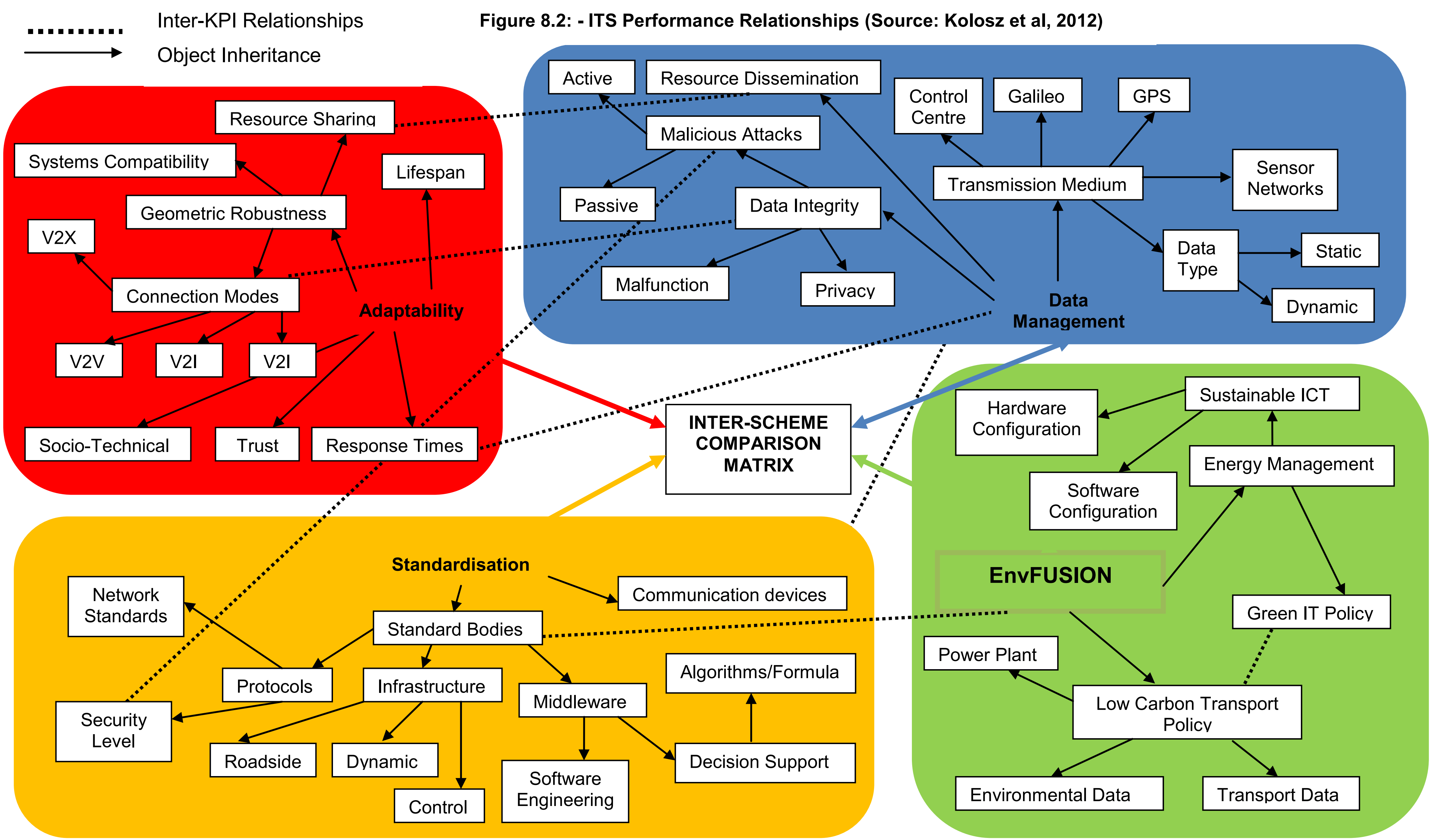
From the information described above, it is possible to identify four major areas of performance within ITS. These areas can be positioned into a group of KPI's each with their own specific attributes. The proposed KPI's are as follows: -

- Data Management and Information Complexity
- EnvFUSION (Integrated Sustainability Assessment)
- Standardisation
- Adaptability

The proposed KPI's represent the general performance cornerstones across four main areas of managing intelligent transport systems within an inter-urban environment, however it may also be possible to The ITS performance management frameworks route to optimisation (Figure 2.6) is expressed via the 'standards highway'. Three of the KPI's will be supported and represented via the standards (a KPI in itself). They represent not only the technical side of maintaining the performance via *continual service improvement* (ITS is built from an IT/technical infrastructure therefore scientific measures must be implemented objectively) but also to reinforce the governance of existing and future transport planning based upon governmental policy (Department of Energy and Climate Change, 2009a).

Figure 8.2 over the next page illustrates the key relationships between the four performance indicators.

Figure 8.2: - ITS Performance Relationships (Source: Kolosz et al, 2012)



In order to ensure ITS achieves acceptable levels of sustainability, performance must be measured from a variety of different perspectives. While it is important for the transport system (including road-side infrastructure and eventually vehicles) to be enhanced using a low-carbon vision, it is also necessary to maintain a carbon neutral data management system (Cabinet Office, 2009; Christensen, 2009; Riaz et al, 2009; Seungdo et al, 2009). According to (2009) Forrester research has estimated that the future market for green IT services will reach around 3 billion pounds by 2013. The use of ICT within intelligent transport provides an integral platform to implement and maintain advanced traffic services, therefore any ICT infrastructure that is directly involved in maintaining transport services must also be environmentally balanced (Ho-Jin and Jong-Tae, 2009).

Whilst a further strand to the research concerns the development of a sustainability index to assess the performance of a scheme in isolation, the focus of this thesis is at the strategic level of all four key performance areas. Given current economic pressures alongside the political imperative to achieve national and international targets relating to energy and the environment, the ability to compare performance across alternative schemes will have considerable impact within the ITS stakeholder community of operators, suppliers, policy makers and funders. The flexibility to incorporate bespoke detail within the ITS-PMF means that the framework as a whole is both adaptable and transferable across regions and countries.

8.4 Management and Assessment of Sustainable Performance Relationships

8.4.1 EnvFUSION Behavioural Relationships

For EnvFUSION, Figure 8.3 illustrates the cause and effect relationships affecting the transition of the road network to a low carbon future from the perspective of a road network operator.

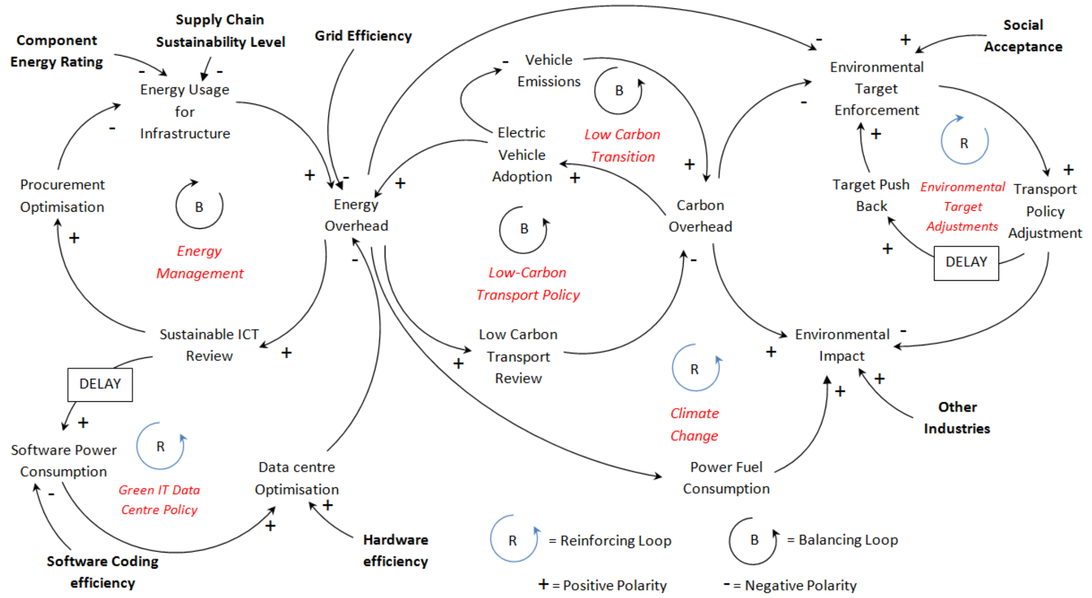


Figure 8.3: - EnvFUSION Feedback Loop (Source: Kolosz et al, 2012)

With reference to Figure 8.3 the low carbon transition features multiple elements of uncertainty which the feedback loop attempts to resolve. The diagram starts with two exogenous (external input) elements - the *Supply Chain Sustainability Level* and *Component Energy Rating* which affect the level of energy that is consumed within the infrastructure. The *Energy Usage for Infrastructure* element relates to the current levels of energy that are used to maintain power within the various components. *Energy Overhead* is the overall level of potential waste energy that exists within the network. Some power that is drawn from roadside components may be due to inefficiency and will have a direct impact on enforcing sectoral environmental targets. *Procurement Optimisation* is based upon an external assessment of the network providers upstream supply chain (a focus for EnvFUSION). A lifecycle assessment of the supply chains emissions may enable the network provider to optimise procurement, thereby reducing the embedded emissions of the ITS infrastructure. Within the ICT data center policy loop, a *sustainable ICT review* is given which is implemented to increase energy efficiency (Murugesan, 2008). The review attempts to increase energy efficiency of both *software energy consumption* (based upon *software coding efficiency*) and *hardware* (facilities and support equipment) efficiency via selecting service providers that meet the required energy efficiency targets of the network provider. Enhancing *data center optimisation* of ICT Service providers influences energy efficiency through the provision of efficient hardware and software equipment that is procured through their own supply chain, however this particular area is not included within the scope of the framework.

In addition to the ICT Review, increasing energy and emissions overheads result in *a low carbon review* which aims to reduce vehicle emissions. This places pressure on manufacturers to produce more energy efficient vehicles which in turn will reduce the carbon output through the introduction of hybrid engines. The *vehicle emissions* element is based upon the number of vehicles taking to the UK roads as well as the effectiveness of the vehicle to reduce its own emissions. Some manufacturers will attempt to introduce fully electric vehicles which will cause a percentage of vehicle owners to push towards *electric vehicle adoption*; however, electric vehicles will require charging from the grid.

This draws more energy directly from the national supply further increasing the energy overhead. Grid efficiency determines the sustainable effectiveness of power production within a sectoral area. As the energy supply to the network increases, the *energy overhead* rises. The *carbon overhead* is the current level of emissions that exist within a region. An increase in carbon overhead underlines the need for a *low-carbon transport review*. The *environmental impact* is based upon all hazardous emissions from the road transport sector and *other industries* that are affecting the state of the ecosystem that are external to the focus of the SD model. The refining of *transport policy adjustment* is based upon historical data and the need to reduce emissions which is key to meeting the targets of the government and EU (Kyoto Protocol etc).

Target push-back is the reconfiguration of the low-carbon policy to achieve the targets at a different date or to sell excess carbon units via emissions trading (one of the tools of the Kyoto protocol)(Huang et al, 2010; Iwata and Okada, 2010; Tietenberg, 2010). The adoption of these targets via *Environmental target enforcement* depends on social acceptance and can be defined as the ability of stakeholders to support and enforce emissions reductions.

Table 8.1 describes the positive/Reinforced loops and negative/balancing loops.

Positive/Reinforced Loop	**Description**
Green IT Data Center Policy	This loop deals with the impact of the network providers data center policy and includes the iterations of data center optimisation. It aims to reduce the energy in IT hardware via removing the bloat in software code. This makes the software easier to compile and manage therefore requires less processing time from the hardware. Within ITS services the impact of ICT is linked with the energy and emissions output of the road-side infrastructure.
Climate Change	This is a simple loop where the planets eco-system cannot handle excess emissions therefore the carbon overheads increase which causes the temperature to rise.
Environmental Target Adjustments	This loop is based upon the UK governments plan to meet baseline carbon reduction targets that were agreed under the Kyoto protocol. However, if the level of carbon is increasing these targets must be pushed back.
Negative/Balancing Loop	**Description**
Low-Carbon Transport Policy	This loop deals with the low-carbon transport policy. It is a culmination of energy and carbon overheads which deal with the solution to adopt electric vehicles. However, this adoption would lead to an even greater demand on the power grid because of the vehicles requiring a charging platform.
Energy Management	This loop concerns itself with the reduction of energy demand via introducing a sustainable ICT review which in turn will lead to reduced energy consumption.
Low carbon Transition	Low carbon transition tracks the gradual decline in road emissions via the introduction of less carbon intensive vehicles.

Table 8.1: - EnvFUSION Positive/Reinforced and Negative/Balanced Loop Description (Source: Kolosz et al, 2012)

8.4.2 Adaptability Behavioural Relationships

For the KPI Adaptability the data elements along with the positive and negative loops are shown in table 8.2. A representation of the KPI feedback loop diagram can be viewed in Figure 8.4.

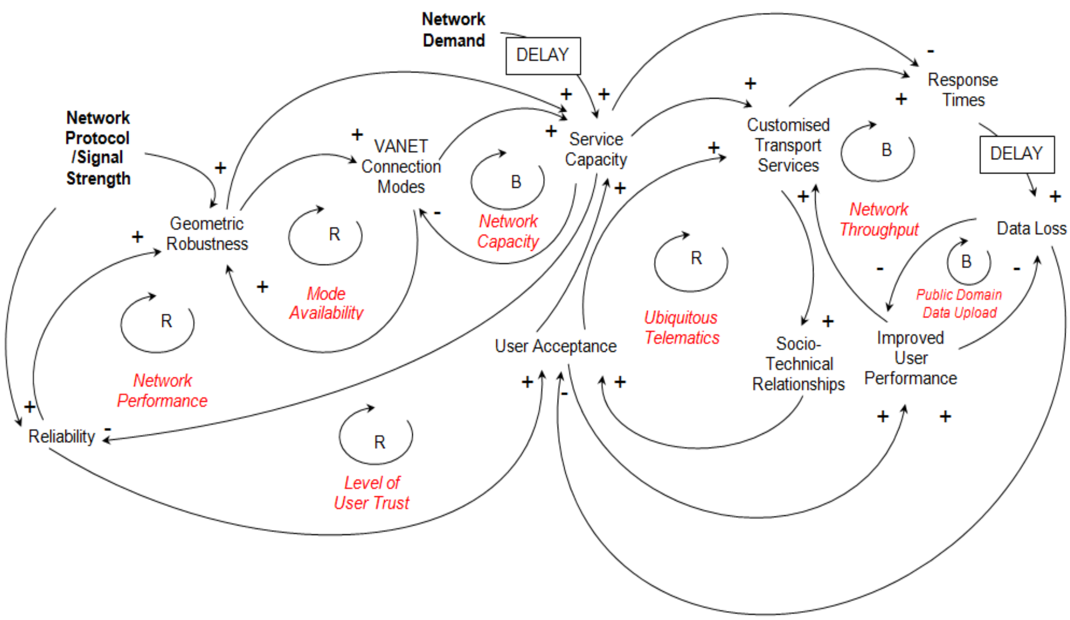


Figure 8.4: - Adaptability Feedback loop

In relation to the endogenous characteristic the 'Adaptability' KPI contains a variety of different elements. *Reliability* can be defined as the overall effectiveness of the services that are being provided to the network. While at a closer level this appears to be ambiguous the system dynamics method allows a fuzzy qualitative analysis and instead focuses on the relationships, however it has been added here in order to give an approximate example of how reliability is affected by the other data elements. *Geometric robustness* as discussed earlier deals with the capability of the wireless network to perform in different environments based upon landscape and weather. *VANET connection modes* determine the different modes of communication that the network supports. *Service capacity* represents the maximum amount of services dependent relative to the number of users that are connected to the system. *User acceptance* is defined by the constant use of a service and the eventual familiarity that is gained from this experience. *Customised transport services* deals with the increase in the type of services offered and the *socio-technical relationships* are instances of 1 user using 1 particular service. *Response times* can be classed as the average time it takes for an instance of a service to reach the desired user. *Data loss* is based upon the likelihood of data becoming lost via transmission causing possible disruption of the service. *User performance* refers to the ability of the user to use a particular service such as message passing and manually identifying an event or incident via a text service etc. Exogenous elements *include network protocol/signal strength* and *network demand* which refer to the overall ability of the network to cope with traffic. Adaptability features a number of cause and effect relationships (Table 8.2).

Positive/Reinforce Loop	Description
Network Performance	Network performance is the basic operational success of the network. It is based upon three relational elements. The loop begins when Network demand encourages the network operators to increase service capacity which in turn decreases reliability due to increased stress placed on the hardware and software. The level of reliability is also dependent on another exogenous element, *Network signal strength.* Reliability will directly affect the ability of the network to endure environmental and geometric events.
Mode Availability	This loop concerns itself with the availability of the different communication modes (V2V, V2I etc). It is based upon two distinct elements; VANET connection modes and Geometric connectivity robustness.
Level of User Trust	User trust depends on the reliability of the service which in turn decides whether the user accepts the new system. User acceptance will increase the workload of the service and more user get accustomed to using it.
Level of Ubiquitous services	The level of customised services that are available will increase the number of socio-technical relationships. These relationships help to increase the amount of data for message passing. As more data becomes available user adoption will increase which in turn will increase the level of customised services.
Negative/Balancing Loop	**Description**
Network Capacity	Network capacity is based upon the current workload increasing the use of different VANET communication modes.
Public Domain Data Upload	This simple loop attempts to counter the impact of data loss triggered by a lack of capacity as more users log on to the network services. Manual data input of traffic events is logged via the user using a nomadic device (V2X).
Network Throughput	When there is an increase in service workload the response times are lowered. This causes a DELAY which may will lead to an increase in data loss. User performance will suffer because of this loss which in turn will have an effect on user adoption.

Table 8.2: - Adaptability Positive/Reinforced and Negative/Balanced Loop

8.4.2 Data Management Behavioural Relationships

For the KPI Data Management the data elements along with the positive and negative loops are shown in table 8.3. A representation of the KPI feedback loop diagram can be viewed in Figure 8.4.

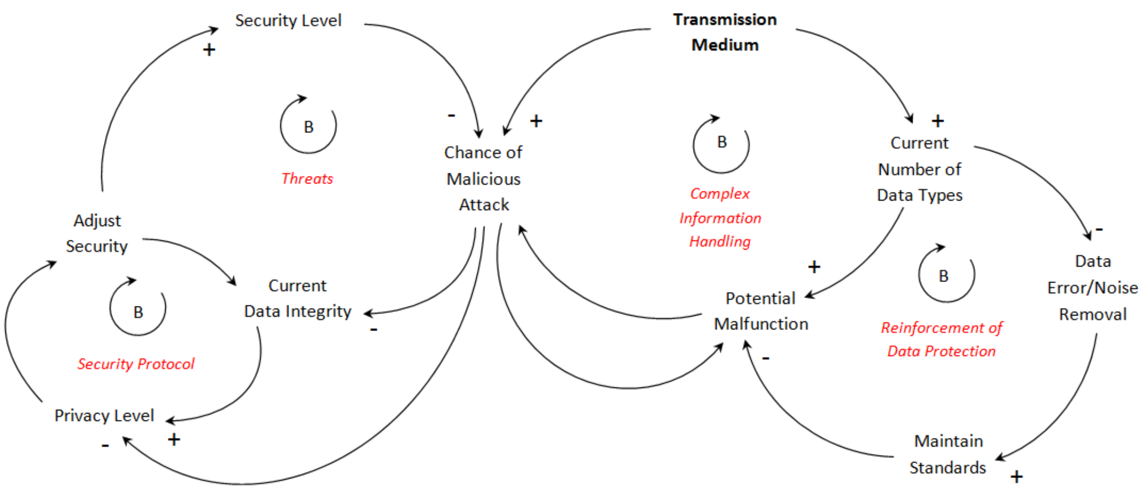


Figure 8.4: - Data management Feedback loop diagram

With regard to the endogenous items in information complexity it is apparent that the more complex a service is, the higher the risk that the service will fail. The *security level* is based upon who has access to what type of data at a specific time and location. For example a user may read and add new data regarding current events to the system via a nomadic device. However, they cannot modify or update existing data. *Security adjustment* attribute will change the security level depending on the likelihood of a malicious attack or when modifications are being made to the network. The *privacy level* identifies how vehicles are seen within the network. This viewpoint is particularly catered for traffic control or a regional control centre. The privacy level could be lowered on a particular vehicle in case of an accident so that the driver of the vehicle can be located. In addition, if a driver has broken the law or is behaving sporadically then the privacy level on that vehicle maybe lowered so that the police can located and question the driver. *Data integrity* may be affected via hackers or other malicious attacks. A *chance of malicious attack* may occur if there is a malfunction or certain aspects of the security system have failed. The *chance of malfunction* may occur if there are a lot of data types or if standards have not been sufficiently inaugurated. *Data types* are based upon different forms of communication and is dependent on the transmission medium that is used. For example, mobile devices will not be able to send more than a few lines of text due to the high latency. GPRS and traditional mobile devices can avoid this since the data is not safety critical and can be sent with a degree of delay. The *maintain standards* element is important in order to ensure the service that is provided ensures a high degree of quality. The *chance of the data possessing errors* or noise is directly attributes to the level of data types and transmission mediums. Users of the road are more likely to input data that may be incorrect due to either misuse or unfamiliarity with the network. Finally, the level of *resource dissemination* is a process where data is filtered and sorted into a meaningful format in order to relay this information to the driver. It should be noted however that this form of central processing and distribution would only be applicable to the traffic control centre for general information. A vehicle would require their own dissemination application.

Exogenous elements include user data input. This is based upon the user utilising a nomadic device to manually notify the traffic control centre or other vehicles within a VSC of certain events that arise while travelling. However, because of laws already restricting use of mobile phones, the actions may have to use voice recognition technology or adapt the use of suitable interfaces to maintain safety and high standards of driving during message passing.

Table 8.3 describes the positive/Reinforced and Negative/Balanced Loops.

Positive/Reinforced Loop	Description
Complex Information Handling	Complex information handling is based upon the transmission medium that is used as well as the current number of data types that is available within the ITS network. Information dissemination plays a key part in managing the loop. As user data gets fed into the system the level of dissemination varies. The more data types that are available the higher chance that a malfunction will occur.
Security Protocols	This loop is based upon the privacy level and the security level requiring change. Firstly, if the privacy level drops due to hacking or other malicious attack there is a DELAY in the time taken to diagnose the problem and reset the security defences.
Negative/Balancing Loop	**Description**
Threat Level	This loop is based upon threat management. The security level is set to reduce the level of malicious attacks. If a malicious attack occurs the data integrity drops and will proceed to reduce user privacy if the attack is aimed at sensitive data in which case there is a high probability that it will.
Dissemination and Data Protection	A high number of data types means that a higher chance of noise and data removal required. If there is a constant persistence of noise and irregularity within the data, network standards should be modified to take this into account.

Table 8.3: - Data Management Positive/Reinforced and Negative/Balanced Loop Description

8.4.4 Standardisation Behavioural Relationships

For the KPI Standardisation, the data elements along with the positive and negative loops are shown in table 5. A representation of the KPI feedback loop diagram can be viewed in Figure 8.5.

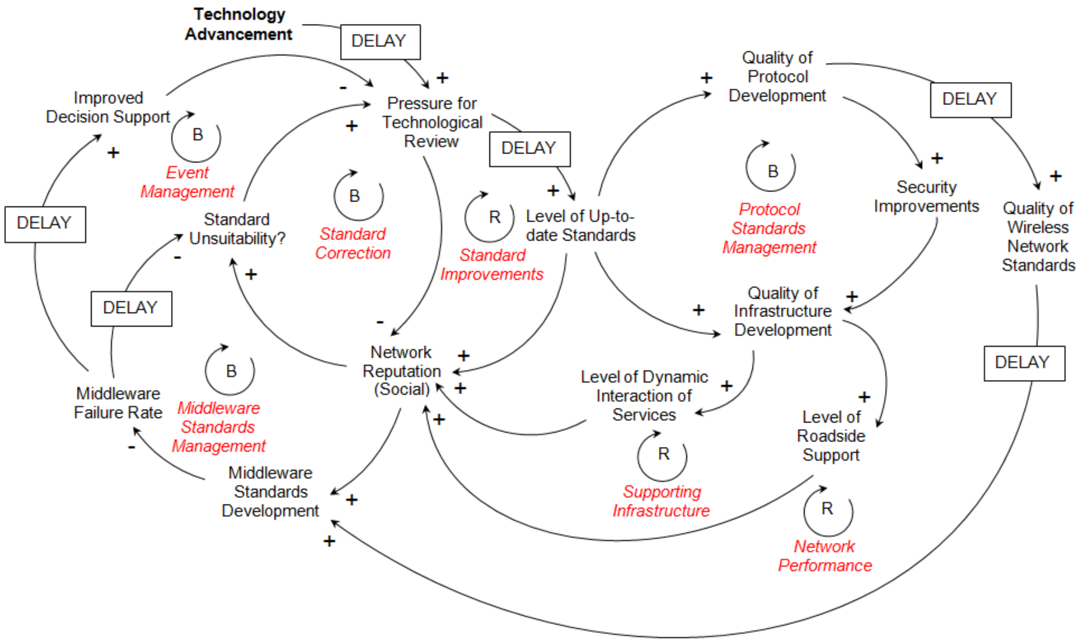


Figure 8.5: - Standardisation Feedback loop diagram

Endogenous items in relation to Standardisation are as follows. *Standard unsuitability derives around* analysing if the performance of standards have caused certain elements of the road network to fail such as the software and hardware of the middleware. *Improved decision support* is derived from the ability to learn and adapt from failures and mistakes as well as technical improvements in the design and support of expert systems. It is important to note that due to a lack of historical data in ITS evaluation the system will attempt to use a logical approach to maintain performance in the road network. However as new technologies are implemented knowledge will be gained on how best to manage new services and the standards to maintain them. The *pressure of a technological review* is based upon currently inefficient or even failing versions of the services used within the network. The higher the pressure the more issues the network is having with the technology that is integrated into the network. The level of *up to date standards* is based upon the monitoring and renewal process of continual service improvement. In addition the standard levels are also in response to user feedback on how the network is performing at that current time as well as advances in technology. Note that there is a delay between the time new services are in development and also the required waiting period of new technology. The *quality of infrastructure development*[1] is based upon maintaining standards as well as services that are currently on-line.

The *quality of wireless network standards* is derived from the development of suitable protocols to handle wireless activity. It is also appropriate to mention the quality will constantly vary depending on the type of connection that is currently taking place. The current *level of roadside support* is based upon the development of sufficient infrastructure that can cope with the demands of ITS ubiquitous services. *Security Improvements* are based upon the likelihood of attack and will lead to a higher quality development of services which may increase social acceptability. The current level of dynamic interaction between services will improve from providing a high quality of infrastructure development and ensuring that all communication modes are available and functioning optimally. *Middleware standards development* is based upon the quality of wireless network standards and ensuring that the appropriate software is being supported by economical and environmentally effective hardware. The middleware failure rate is based upon a lack of good quality standards development for middleware services. The Network reputation will be affected by most of the elements listed here. However, three

[1] Note that the author is discussing the maintenance of infrastructure via the electronic services that are distributed to them rather than the 'physical' aspect.

elements will direct the reputation significantly, which are levels of roadside support, the level of dynamic interactive services and finally the level of up to date standards. Finally, the *quality of protocol development* will be based upon sufficient levels of knowledge of current IT Services (bespoke and in-house) and cost-efficient technology.

Table 8.4 describes the positive/Reinforced and Balanced/Negative loops.

Positive/Reinforced Loop	**Description**
Network Performance	The network performance is based upon the quality of wireless network standards. Since the transport infrastructure will depend entirely on the wireless protocols within a VANET system, it is no coincidence that the development of middleware standards will be affected.
Standards Improvement	Standard improvements are based upon how up to date current versions are applied to the network. Standards will also have a direct impact on the reputation of the network. There is a delay between the technological review and the actual update of standards.
Supporting Infrastructure	Another important factor is the ability to provide high quality infrastructure services for the road-side infrastructure so that breakdowns are handled within the shortest possible time frame. This loop also has a positive influence on the reputation of the network.
Negative/Balancing Loop	**Description**
Event Management	Event management is based upon the learning process of making decisions on the control of IT based services. Because no historical data for ITS management exists, an iterative learning process will take place that will build a knowledge base of past use. In the beginning however, decisions are made logically using conventional traffic management software in order to convey control through the use of ubiquitous services.
Standards Correction	This loop describes the process to reprimand and modify standards that have causes the network to fail. Due to this failure there is pressure on performing a technological review which will begin to affect the networks reputation via the media. a decision is then made on the standards suitability.
Middleware Standards Management	For middleware standards management a social analysis is taken place to determine if the current IT services are gaining support and work well with the users of the transport network. Standards development then takes place. An immediate advantage comes in the form of a lower middleware failure rate. The standard is cross-checked to determine suitability.
Protocol Standards Management	The loop begins with an analysis to determine if the necessary standards are up to date. At this stage the quality of the standards are determined and any changes that need to be made must be managed at this stage. If the standards are of a high quality an immediate advantage will be enhanced security as the standards will take into account the latest attacking threats which are quickly adjusted from an IT perspective.

Table 8.4: - Standardisation Positive/Reinforced and Negative/Balanced Loop Description

8.5 Inter-Scheme Comparison Matrix

8.5.1 Overview

An inter-scheme comparison matrix will be created in order to correlate the data between the four KPI's. It will also include targets set by the government (baselines) and relationships between the four areas for performance analysis. An evaluation of the four KPI's via the data produced within the matrix will then be conducted to determine if the analysis has met its objectives. One of the main benefits of the matrix is the ability to compare between various schemes in a cost effective manner through developing strategic criteria from existing data. Strategic road network operators may request from their upstream suppliers data regarding the performance of the road-side equipment for example, although an agreement will need to be made between the two entities as to the integrity and validity of the data to be extracted.

The inter-scheme comparison matrix attempts to exhibit a granularity that allows geographical identification of poorly performing sectors. For example, a particular junction or link within a network can be scrutinized. The three layered framework, supported by the EnvFUSION socio-economic and environmental assessment allows stakeholders to drill down to understand the root cause of a poorly performing sector and allow comparison between similar links or junctions. The direct benefits of this approach is that network operators may rank and identify elements of sustained optimal performance which can be immediately applied to poorly performing ITS schemes at the microscopic (road-side infrastructure instance such as a single gantry) or the macroscopic level i.e. the UK's managed motorway ITS scheme.

8.5.2 Matrix Characteristics

The scheme comparison matrix aims to follow the general characteristics of a multi-criteria performance matrix with some methodological development represented via the three performance layers. According to (2009) a Multi Criteria Analysis (MCA) features a traditional performance matrix which possesses the following attributes. Each row may describe one of the individual ITS schemes that are being considered. Each column corresponds to a criterion, or performance dimension which is considered important to the comparison of different schemes. Various criteria are developed which are decided by the road network operator depending upon their level of focus. For example, from a sustainable perspective, the power consumption of lighting within the scheme as well as the power utility rating which connects the grid to the infrastructure may fit into this category. Finally, the entries in the body of the matrix assess how well each option performs with respect to each of the criteria. In the case of multiple evaluators various letter codes are given to differentiate the stakeholders of the scheme. The individual measurements are often numerical but can materialise in color coded or bullet-point style indicators. The weights will feature a range of 0 to 100 with the least being 0. The weights are then assigned in order to provide 'scope' and relevance to the numerical figures.

The matrix for the KPI performance measures will be developed using the methodological approach for the creation of an inter-scheme matrix as detailed in the traditional MCA literature. While traditional matrices have a flat based structure, the development of the inter-scheme comparison matrix will be significantly more detailed, therefore it may be desirable to develop the KPI suite in a literal three-dimensional format. Because the KPI's are generic and cater for a wide variety of ITS technologies, the tool will have a superior advantage over current transport planning and ITS component/Infrastructure selection.

The advantage of using such a format is three-fold. Firstly it allows for a greater sense of depth in measuring performance which will aid better decision making. Secondly, because of its multi-dimensional properties, the inter-scheme comparison matrix will be able to cater for a wider group of bodies that are linked to ITS performance management. For example, the strategic layer gives an overview of current trends in comparing the performance of certain ITS technologies such as Galileo etc. The tactical layer will be able to move into greater depth within a KPI and can focus on more specific issues such as understanding response times in a specific environment. Finally, the operational layer would allow a user to customise the KPI using metrics, environmental assessment tools and measures.

The final benefit would be the ability to measure performance under a low-carbon future, thus any technology that is developed would be given a rating to reflect the predicted impact the technology would have upon the environment. More specifically, the level of carbon that currently exists in the region or zone could be measured. The development of an inter-scheme comparison matrix could play a pivotal role in the future pathways for many governments internationally with a desire to attain a low-carbon future.

8.5.3 Overview of Matrix Data Flow

As ITS projects are based largely on decoupled IT virtual services, the data between ITS attributes and actors is likely to vary as time passes. Figure 8.6 illustrates the general data flow of the KPI' when connected to the matrix. The perspective is perceived from viewing the ITS-PMF ‘top down’, with the four key performance cornerstones visible.

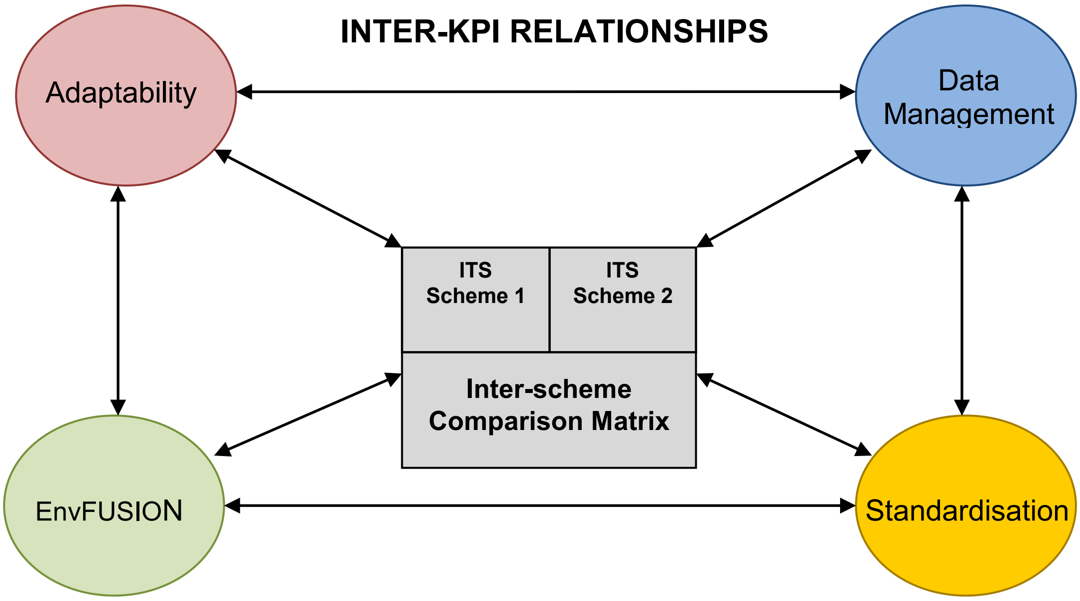


Figure 8.6: - Inter-Scheme Comparison Matrix and KPI Data Flow (Source: Kolosz et al, 2012)

Data that is fed into the performance management framework will first be designated to a KPI based upon the type of attribute the data belongs to. Attributes will share common relationships with other attributes in different KPIs. As discussed earlier, it is important to note that the relationships between KPI's must be mapped in order to determine the cause and effect relationships from indirect and direct scenarios such as those shown in figure 2. For example, some attributes such as the security level within the network will directly affect the integrity of data, therefore performance levels may fluctuate depending upon the relationships between the KPI's. The advantages of this approach are that it tries to remove aspects of policy resistance that arise from underdeveloped or hidden reactions to data elements which is one of the key goals of the SD methodology.

8.7 Chapter Summary

This chapter has introduced an integrated strategic performance toolkit known as ITS-PMF. An overview of the strategic performance management framework has been given indicating EnvFUSION as one of four cornerstones for managing intelligent transport technologies. Identifying the cause and effect relationships of the low carbon transition provides a rare glimpse of transparency to stakeholders involved in managing the road network which can assist in developing criteria for a robust ITS scheme comparison. By comparing ITS schemes, crucial benefits are realised such as the triangulation of energy and emission hotspots, data can be quickly generated and procured at a low cost and the use of a three-dimensional performance assessment allows the framework to adapt to the needs of all stakeholders involved within ITS performance evaluation. Finally, the comparison matrix also exhibits a granularity that allows geographical identification of poorly performing sectors at the microscopic and macroscopic level.

To date, there is still no real commercially viable alternative for assessing the embedded and consumed emissions of physical transport infrastructure and their ICT data links. The proposed strategic toolkit aims to provide the methodological foundations in order to improve this paucity of integrated and cooperative inter-scheme assessment tools. It is important to note that without the contribution of such tools as ITS-PMF and its KPI method - EnvFUSION, technological and cooperative improvement of the transport network may be overshadowed by the environmental deficit, currently shaping our future life.

"The impact assessment of ITS applications is an essential step within the process of implementation policies creation and application; it is however not a stand-alone one. Its success depends on the ability of the planners to create clear and detailed implementation scenarios, that can support the comparative evaluation procedure that needs to follow, to derive to implementation priorities and decisions" (Bekiaris et al, 2004).

Chapter 9 - Conclusions and Recommendations

In this concluding chapter, an evaluation of the thesis, study and the sustainability performance framework was carried out. The research objectives were cross-referenced with the work performed to determine the level of success. The contribution of the research to the knowledge base of the literature is discussed and directions of future research are explored.

9.1 Thesis Summary

The thesis 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 results of the first part of the study, the road-side infrastructure contributed around 9% (1.647 kilo-tonnes of CO_2 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 75 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 results of the second part of the study show that ATM will offset greenhouse gas emissions by 99 kilo-tonnes of CO_2 equivalency over a 25 year lifespan. This reduction compared with the first study has taken into account the expected improvement in vehicle technology. AHS is anticipated to save 280 Kilo-tonnes of CO_2 equivalency over 15 years of operational usage. However, this offset is largely dependent on assumptions such as the level of market penetration. Nevertheless, the results of the ITSI index indicate a high level of future performance is anticipated concerning emissions reduction and in terms of safety, energy conservation and the monetary perspective.

This thesis has also introduced an integrated strategic performance toolkit known as ITS-PMF. An overview of the strategic performance management framework has been given indicating EnvFUSION as one of four cornerstones for managing Intelligent Transport technologies. Identifying the cause and effect relationships of the low carbon transition provides a rare glimpse of transparency to stakeholders involved in managing the road network which can assist in developing criteria for a robust ITS scheme comparison. By comparing ITS schemes, crucial benefits are realised such as the triangulation of energy and emission hotspots, data can be quickly generated and procured at a low cost and the use of a three-dimensional performance assessment allows the framework to adapt to the needs of all stakeholders involved within ITS performance evaluation. Finally, the comparison matrix also exhibits a granularity that allows geographical identification of poorly performing sectors at the microscopic and macroscopic level.

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. 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 rollout of a number of Intelligent Transport Systems is already underway in many countries, with new and innovative ITS schemes anticipated in both the near term and longer term future. What is required now is an improved understanding of the expected socio-economic and environmental performance of such ITS technologies. The second part of the case study in the thesis has considered one future scenario in terms of the implementation of new technology. Many scenarios are possible to reflect potential changes at both the macroscopic level (the services the technologies deliver) and the microscopic level (improvements in material production, vehicle technology and electrical devices etc). Widespread deployment of the new ITS applications in practice is, of course, dependent upon a number of factors. The macroeconomic landscape and the global economic downturn affect R&D investments, which may impact on the long-term needs of AHS. Interoperability and standardisation issues need to be resolved to achieve large-scale integration of vehicle and transport infrastructure and provision of services over different platforms and countries. In particular, in-vehicle systems face the hurdle of requiring 100% deployment in motorized vehicles to function. However, this penetration problem is a common issue for a variety of other Vehicle-2-Vehicle or Vehicle-2-Infrastructure applications. Safety-related applications are a particular example that requires high penetration rates for effectiveness and are promoted for their evident advantages. Reaching this level of deployment may require legislative action, for example for retro-fitting of existing motorized vehicles with appropriate ITS systems.

The EnvFUSION framework has been designed so that it can be applied to urban areas and technologies in addition to highways, provided that the data is available and in order to assist in decision making. The main strength in the framework is, however, the ability to take uncertain or conflicting data and estimate performance over time using dynamic targets. The framework is therefore flexible and can be adapted to the needs of the user and the context, whether at the regional, national or international level.

9.2 Achievement of Research Objectives

The research objectives that laid out the path to completion were cross-referenced with the actual research outcomes and indicative evidence of completion. As stipulated in Chapter 1, there were six research objectives. The initial goal was to identify the main weaknesses of ITS appraisal/evaluation frameworks in terms of environmental and socio-economic perspectives. After the weaknesses were identified, proposed solutions were formulated which provided the foundation for the creation of a new sustainability framework which would aim to assess ITS for what is - a system. This process was carried out in Chapter 2 and is summarised in Table 2.3.

The second research objective was to evaluate a number of ESAT tools and develop an integration strategy so that the selected methods could operate in unison in order to resolve traditional deficiencies of when they are being used in isolation. This was carried out in Chapter 4. The third research objective was to design and develop a sustainability performance framework based upon the selected methods from the previous chapter. The data collection strategy from Chapter 5 illustrates how the criteria was selected as well as how the methods operate. Part of this chapter made up the first part of the case study which was the assessment of ITS systems currently in operation. Active Traffic Management on the M42 was selected as the focal area and the results were presented in Chapter 6. These results were accepted for publication in Kolosz et al (2013a). The fourth research objective dealt with the second part of the study which was an evaluation of forecasted ITS services. Intelligent Speed Adaptation and Automated Highway Systems were simulated on the M42 using a system dynamics model and a consequential lifecycle assessment. These results were accepted for publication in (Kolosz et al, 2013b) The fifth research objective was to develop an inter-scheme comparison method which would take into account socio-technical criteria which are connected through the use of feedback loops. This was carried out in Chapter 8 and the results were accepted for publication in Kolosz et al (2012). The final research objective was the evaluation of the thesis, its contribution to the wider literature, and directions for future research. Table 9.1 illustrates the level of success.

Research objective	Initial research problem	Research solution/outcome	Evidence of completion/success
RO1: Identify main weaknesses of ITS appraisal frameworks and propose novel solutions to reduce these weaknesses.	Limited frameworks were available. There has been little evaluative work carried out on assessing the performance of ITS as a system. Lack of historical data in terms of assessing the sustainability of ITS services.	an authoritative literature review of over 300 papers from 1979-2013 is reported in chapter 2 and throughout the thesis. Of these papers, 10 related to ITS evaluation frameworks.	Chapter 2: Defining Sustainability Performance for Inter-urban intelligent transport.
RO2: Evaluate current environmental analysis and decision tools for assessing the sustainability of ITS Services.	Current environmental analysis tools do not provide relationships between ICT and transport data. Tools that are standalone possess weaknesses which must be reduced.	A further review of ESAT tools featuring over 250 papers. An integration strategy allowed weights to be combined successfully for the study.	Chapter 4: A Review of Sustainability Assessment Approaches for Inter-Urban Intelligent Transport; Chapter 5: Development of the study and data collection strategy.
RO3: Design and develop EnvFUSION model to accurately assess the sustainability of current ITS services.	Current appraisal frameworks have a variety of weaknesses which must be resolved to improve sustainability assessment of currently implemented ITS systems.	Results of the data fusion indicate the sustainability of ATM is 'medium' with the least performing criterion being the data center energy consumption. The most performing criterion was cost.	Chapter 5: Development of the study and data collection strategy; Chapter 6: Evaluation of current inter-urban ITS systems: Active Traffic management; **Main results published in journal article (Kolosz et al, 2013a).**
RO4: Design and develop EnvFUSION model to accurately forecast the sustainability of future key ITS services.	Current forecasting methods tend to focus on the road and improvements in efficiency as opposed to also estimating the environmental impact of the ICT data center and consequential modelling.	Results indicate that the M42 will feature savings from 99 Kilo-tonnes of CO_2 equivalency from ATM to 250 Kilo-tonnes through the use of AHS.	Chapter 5: Development of the study and data collection strategy; Chapter 7: - Evaluation of Future Inter-Urban ITS Systems: ISA and AHS; **Main results published in journal article (Kolosz et al, 2013b)**
RO5: Identify and model ITS socio-technical parameters for inter-scheme comparisons.	Little understanding of relationships between environmental and socio-technical criteria. No relationships with standards enforced by legislation.	The inter-scheme comparison matrix is a skeletal framework which can identify emissions hotspots between schemes.	Chapter 8: - Modelling ITS Socio-technical Parameters for Inter-Scheme Comparisons; **Material published in conference paper (Kolosz et al, 2012).**
RO6: Evaluate the sustainability framework and relate the results in the context of the wider ITS appraisal research.	There was currently no rigorous evaluation of ITS appraisal.	A rigorous ITS approach has been performed and evaluated within the context of the thesis.	Chapter 9: - Conclusions and Recommendations.

Table 9.1: - Evidence that the research objectives have been achieved

Another component for measuring success was to determine if the deficiencies of current ITS evaluation frameworks were resolved. This involved cross-referencing the weaknesses and the proposed solutions with the evidence provided. Table 9.2 illustrates the 11 deficiencies of ITS evaluation, the solution that was carried out and the evidence of success.

Deficiency	Proposed solution	Evidence of success
Linear economic ITS benefit characterisation.	Each index value weighted and given an normalised performance value so that combination can be achieved through a holistic performance indicator.	Each of the 10 criteria has been weighted through three stages via the analytical hierarchy process, distance to target and information fusion through Dempster-Shafer theory. This was carried out in Chapter 6 (section 6.3) and Chapter 7 (section 7.5).
Limited geographical focus.	Assess performance at the system level taking into account all services that are linked to the ITS scheme such as the data center etc.	The data center, road-side infrastructure and vehicle emissions were combined to determine performance. Results are available in Chapter 6 (section 6.2.2)and Chapter 7 (section 7.3.1)
Conflicting stakeholder involvement.	Allow performance evaluation to be made by consolidating opinions from multiple stakeholders into a method which can handle conflict.	Dempster-Shafer theory was used to perform probabilistic data fusion on independent sources in order to handle conflict. This was carried out in Chapter 6 (section 6.3) and Chapter 7 (section 7.5).
Decision making isolated at various levels of implementation.	Introduce three separately stacked layers for each level of focus and show the contribution of the ITS schemes performance between each layer.	Proposed a strategic performance management framework with three main focal areas: strategic, tactical and operational. This was proposed in Chapter 8 (section 8.2). EnvFUSION was defined in the tactical focal layer.
Data collection uncertainty.	Evaluation should include rigorous sensitivity testing and not apply false precision to the estimated environmental and socio-economic impacts.	The Ecoinvent lognormal distribution method was used to assess the uncertainty of the LCA inventory analysis and was carried out in Chapter 6 (section 6.2.6).
Elements of ITS calculated in isolation.	Integrate the environmental lifecycle results of the ICT data center, vehicle emissions and embedded emissions of road-side infrastructure to provide a cross-sectional contribution of total emissions generated from the ITS service.	The data center, road-side infrastructure and vehicle emissions were combined to determine performance. Results are available in Chapter 6 (section 6.2.2) and Chapter 7 (section 7.3.1)
Limited assessment of greenhouse gases.	Convert greenhouse gas emissions into Global warming potentials where available to maximise the accounting accuracy of the ITS schemes contribution to climate change.	The CML impact assessment method was used to determine the global warming potential calculated over a period of 100 years.
No scheme comparisons.	An inter-scheme comparison supermatrix containing normalised ITS performance indexes between schemes for each category.	An inter-scheme comparison matrix was proposed in Chapter 8, section 8.5.
Limited socio-technical analysis.	Define performance areas and performance relational analysis using dynamic modelling methodologies.	System dynamics was used to create relational feedback loops from the four criteria. This was carried out in Chapter 8 (section 8.4).
Monetary environmental benefits inaccurate over long-term.	Apply dual discounting for future ITS schemes in order to measure environmental cost savings for periods of more than 20 years.	A cost benefit analysis using dual discounting was developed and applied to ATM, ISA and AHS. The results are illustrated in Chapter 7, section 7.4.
Lack of linkage between regional and national emission targets.	Weight the level of emissions offset against the distance of a specified target being reached. Introduce different weights for regional, national and international perspectives.	A distance to target method was created in order to align ITS performance with regional, national and international contexts. This was carried out in Chapter 6 (section 6.3) and Chapter 7 (section 7.5).

Table 9.2: - Evidence of success in the proposed solution to ITS evaluation

9.3 Contributions to Knowledge

The research has provided several contributions to the ITS literature. Some of the key contributions are described in Table 9.3.

Original Contribution	Evidence	Importance
New performance framework which resolves current deficiencies in ITS appraisal (Table 9.2).	1 journal article published.	This contribution was important due to the many deficiencies of ITS evaluation frameworks. Resolving these deficiencies greatly improved the accuracy of estimating sustainability.
New forecasting method designed to estimate future sustainability performance.	1 journal article published.	The forecasting method allows ITS services to be assessed regardless of implementation type. This was traditionally challenging due to the wide variety of ITS technology configurations.
Performed an evaluation of ITS at the system level which allows for a prioritised comparison between the data center, infrastructure and vehicle emissions	Chapter 6: Evaluation of current inter-urban ITS systems: Active Traffic management; Chapter 7: - Evaluation of Future Inter-Urban ITS Systems: ISA and AHS.	The change in focus to the system level allows the full range of services to be assessed which results in more accurate emissions estimates.
The combination of methods: LCA, DTT and DS/AHP is a 'first' in the known literature which reduces the weaknesses of each individual method to a large extent.	Chapter 5: Development of the study and data collection strategy.	It is now known that these combination of methods can work together which enhances the environmental modelling literature and reduces the drawbacks of the methods working in isolation.
Carried out an extensive review of Environmental System Analysis Tools (ESAT) within the context of estimating the performance of Intelligent Transport services. Such a review has never been carried out on a large scale.	Chapter 4: A Review of Sustainability Assessment Approaches for Inter-Urban Intelligent Transport.	It was important to consolidate the various studies of ESAT tools applied to ITS to determine the usefulness of each method as well as to select the most appropriate methods.
Designed four distinct performance indicators and applied them through an inter-scheme comparison matrix which allows stakeholders to compare the performance of different ITS types.	Chapter 8: - Modelling ITS Socio-technical Parameters for Inter-Scheme Comparisons. Published conference paper.	Understanding the relational feedback of ITS will help the design of future ITS technologies as well as assist in estimating the performance from a technical perspective.
Expanded the methodology of the traditional distance-to-target method to take into account multiple data types.	Chapter 6: Evaluation of current inter-urban ITS systems: Active Traffic management; Chapter 7: - Evaluation of Future Inter-Urban ITS Systems: ISA and AHS.	Expanding the methodology of distance-to-target methods enables quantitative and qualitative data types to be weighted via targets. Improved integration and normalisation.
Developed a system dynamics software application for estimating ITS performance with the option to develop various scenarios.	The application is available on a CD in a pocket to the back of the thesis. Also available on request.	The software application enables consolidation of environmental calculations in one interface. It is important due to the complexity of the data collection process.

Table 9.3: - Contributions to Knowledge

9.4 Limitations and signposts to 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. Reliability issues within deficient data sources and the use of probabilistic data methods should be explored more thoroughly. One issue that exists in the EnvFUSION framework is the assessment of vehicle emissions in the macroscopic frame using average vehicle speed. This was due to two factors. Firstly, microscopic traffic models when projecting over a long time period become unmanageable and inaccurate due to the vast quantities of data sets and forecasting algorithms required (Smit et al, 2010). Although this issue was resolved when assessing currently implemented ITS due to the use of past historical data, (i.e. traffic growth is fixed and the results are summed over 15 years), the framework could be adapted to pick up more finer performance characteristics in the microscopic frame. Recent research such as Ramasso (2007) focused on assigning a belief function to continually varying temporal states. A Transferable Belief Model (an enhancement of Dempster-shafer theory although probability is dissociated from the model) is a mathematical theory of evidence which was used to assess the temporal states of human motion using Forward-Backward-Viterbi procedures. These techniques could be applied to estimating vehicle emissions using limited data sets and to also project them forward via filtering several belief functions. This would allow a thorough estimate at the microscopic level over a longer time frame which would increase the accuracy of the forecast.

Due to time constraints, a more detailed consequential forecast taking into account changes in materials, new production technologies and alternative vehicle energy sources proved difficult to undertake. 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 including materials (Chen et al, 2012; Stasinopoulos et al, 2012). In addition, a life cycle cost analysis could be undertaken to monetise the entire lifespan of current and future schemes (Lipman and Delucchi, 2006). Again, a lack of time and data on inventory unit processes made implementing this method difficult.

The scope of the research could be extended to take into account urban based systems. As stated earlier in the report, EnvFUSION can estimate all forms of ITS service provided that a minimum amount of data is available to model it. A dynamic cityscape such as London could be investigated to determine what the impact of ITS would have in terms of environmental, economic and socio-technical change. Once again this depends upon the amount of data that is available and also the amount of time available to the researcher. Another limitation is that the inter-scheme comparison matrix has not been tested using real world studies. Future research would expand on the other three performance indicators in more detail so that a more expansive framework could be applied to assessing socio-technical performance of ITS services using inter-scheme comparisons. The VENSIM model used to create a system dynamics simulation of the M42 using the EnvFUSION framework should be developed into a fully functional piece of software with its own user interface. This would also include the inter-scheme comparison matrix. Providing an integrated piece of software was attempted early on in the research, although the weaknesses of VENSIM made implementing DST impossible due to its inability to process data past the sixth significant digit (DST requires much higher processing accuracy to perform information fusion), therefore the software should be implemented through a more generic programming language such as C++ or JAVA SDK's.

The methodology used to calculate the basic probability assignments in DST currently relies heavily on ad-hoc scoring and the subjective opinions of experts. Improvements to the methodology of the initial probability assignment based upon a defined scoring system may enhance the accuracy and consistency of the initial performance observation. This limitation however is alleviated somewhat by the use of AHP and DTT in an effort to provide quantitative support to subjective decision making.

Finally, the work will consider embodied emissions of ICT, although this research area is relatively new and the supporting evidence sparse to date (Yi and Thomas, 2007; Shah et al, 2009; Higgs et al, 2010; Grimm et al, 2012).

9.5 Final Overview

In this chapter, an evaluation of EnvFUSION and the results of the case study has been performed. The level of success has been estimated in terms of research objectives and the resolution of weaknesses in ITS appraisal within the wider literature. Several contributions to knowledge have been stated illustrating a wide range of enhancements to ITS evaluation as well as methodological improvements to methods which operate independently. The limitations and future work also shows promise in terms of improvement of the method and the potential for further contributions to knowledge is high.

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Appendix A: ATM Gantry Production Data and Energy Requirements

Gantry Section	Description	Steel Grade	Density	QTY	Dimensions
Trestle (T1)	Square Hollow Section	S355J2H	7.85	2	400*400*20 (360*360)
	-	S355J2H	7.85	1	350*350*16 (318*318)
	Rectangular Plate	S275J2G3	7.85	2	900*700*75
	-	S275J2G3	7.85	2	700*700*50
	Flat Plate	S275	7.85	2	60*6
	Rolled Steel Angle	S275	7.85	2	60*60*6
	-	S275	7.85	1	60*60*6
Trestle (T2)	Square Hollow Section	S355J2H	7.85	2	400*400*20 (360*360)
	-	S355J2H	7.85	1	350*350*16 (318*318)
	Rectangular Plate	S275J2G3	7.85	2	900*700*75
	-	S275J2G3	7.85	2	700*700*50
	Flat Plate	S275	7.85	2	60*6
	Rolled Steel Angle	S275	7.85	2	60*60*6
	-	S275	7.85	1	60*60*6
MS4 Frame	Square Hollow Section	S355J2H	7.85	1	160*160*10 (140*140)
	-	S355J2H	7.85	1	160*160*10 (140*140)
	-	S355J2H	7.85	3	140*140*12.5 (115*115)
	-	S355J2H	7.85	4	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	Rectangular Plate	S275J2	7.85	1	130*275*6
	-	S275J2	7.85	2	128*128*6
	Flat Plate	S275	7.85	2	50*6
	Rectangular Plate	S355J2	7.85	4	148*148*10
	-	S355J2	7.85	6	117*283*10
	-	S355J2	7.85	6	210*290*10
	-	S355J2	7.85	6	210*298*10
	Neoprene Strip	N/A	0.1	12	80*5
	20 Sq Bar	S275	7.85	12	20*80
MS4 Frame 2	Square Hollow Section	S355J2H	7.85	1	160*160*10 (140*140)
	-	S355J2H	7.85	1	160*160*10 (140*140)
	-	S355J2H	7.85	3	140*140*12.5 (115*115)
	-	S355J2H	7.85	4	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	-	S355J2H	7.85	1	120*120*6.3 (107.4*107.4)
	Rectangular Plate	S275J2	7.85	1	130*275*6
	-	S275J2	7.85	2	128*128*6
	Flat Plate	S275	7.85	2	50*6
	Rectangular Plate	S355J2	7.85	4	148*148*10
	-	S355J2	7.85	6	117*283*10
	-	S355J2	7.85	6	210*290*10
	-	S355J2	7.85	6	210*298*10
	Neoprene Strip	N/A	7.85	12	80*5
	20 Sq Bar	S275	0.1	12	20*80
Main Truss	Square Hollow Section	S355J2H	7.85	4	200*200*10 (180*180)
	-	S355J2H	7.85	4	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	68	80*80*6.3 (67.4*67.4)
	Rectangular Hollow Section	S355J2H	7.85	18	150*100*10 (130*80)
	-	S355J2H	7.85	17	120*80*10 (100*60)
	-	S355J2H	7.85	2	120*80*10 (100*60)
	-	S355J2H	7.85	17	120*60*8 (100*40)
	-	S355J2H	7.85	16	120*60*8 (104*54)
	-	S355J2H	7.85	2	120*60*8 (104*44)
	Rectangular Plate	S355J2	7.85	14	170*150*20
	Lintel	S355J2	7.85	8	150*150*12
	-	S275	7.85	2	100*65*8
	-	S275	7.85	2	100*65*8
	-	S275	7.85	4	60*60*6
	Rectangular Plate	S355J2	7.85	28	170*170*12
	-	S275	7.85	2	160*271*4
	-	S275	7.85	1	620*710*6
	-	S275	7.85	1	540*1110*6
	-	S355J2	7.85	4	225*225*20
	-	S355J2	7.85	4	180*200*20
	-	S355J2	7.85	4	70*165*20
	-	S355J2	7.85	4	70*165*20
	Lintel	S275	7.85	4	150*75*10
	-	S275	7.85	19	40*40*5

Gantry Section	Description	Steel Grade	Density	QTY	Dimensions
Truss (cont..)	-	S275	7.85	4	40*40*5
	-	S275	7.85	2	40*40*5
	Rectangular Hollow Section	S275J2H	7.85	2	50*50*5 (40*40)
	Flat Plate	S275	7.85	2	60*6
	Lintel	S275	7.85	18	40*40*5
	Rectangular Plate	S275	7.85	1	600*750*6
	Lintel	S275	7.85	4	100*65*8
	-	S275	7.85	1	60*60*6
	-	S275	7.85	1	60*60*6
	M8 Bolts *25	4.6	7.85	4	M8 Bolts * 25
	Rectangular Hollow Section	S355J2	7.85	2	50*50*5 (40*40)
	-	S355J2	7.85	4	50*50*5 (40*40)
	-	S355J2	7.85	2	50*50*5 (40*40)
Header Rail	Lintel	S355J2	7.85	1	150*75*10
	-	S355J2	7.85	1	150*75*10
	-	S355J2	7.85	1	150*75*10
	-	S355J2	7.85	1	150*75*10
Sign Post	Universal Beam	S355J2	7.85	4	254*146*37
	-	S355J2	7.85	3	254*146*37
	Rectangular Plate	S355J2	7.85	7	187*170*30
	-	S355J2	7.85	7	281*170*30
	-	S355J2	7.85	7	246*146*10
	-	S355J2	7.85	1	132*234*10
Gantry End 1	Rectangular Plate	S275J2G3	7.85	1	900*700*75
	-	S275J2G3	7.85	1	700*700*50
	Square Hollow Section	S355J2H	7.85	2	400*400*20 (360*360)
	-	S355J2H	7.85	2	350*350*16 (318*318)
	Rectangular Plate	S275J2G3	7.85	1	400*600*75
Gantry End 2	Rectangular Plate	S275J2G3	7.85	1	900*700*75
	-	S275J2G3	7.85	1	700*700*50
	Square Hollow Section	S355J2H	7.85	2	400*400*20 (360*360)
	-	S355J2H	7.85	2	350*350*16 (318*318)
	Rectangular Plate	S275J2G3	7.85	1	400*600*75
AMI Fr HS*2	Square Hollow Section	S355J2H	7.85	1	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	2	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	2	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	1	80*80*6.3 (67.4*67.4)
AMI F R L*6	Square Hollow Section	S355J2H	7.85	1	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	2	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	2	80*80*6.3 (67.4*67.4)
	-	S355J2H	7.85	1	80*80*6.3 (67.4*67.4)
AMI 'Y' Frm*8	Flat Plate	S275	7.85	1	75*6
	-	S275J2G3	7.85	3	80*10
	Square Hollow Section	S355J2H	7.85	2	75*75*6 (63*63)
	Flat Plate	S275	7.85	1	80*10
	Square Hollow Section	S355J2H	7.85	1	75*75*6 (63*63)
	Flat Plate	S275	7.85	3	75*6
	Flat Plate	S275	7.85	3	150*6
	Flat Plate	S275	7.85	1	80*6
Cable Tray	Medium Flange	S355J2	7.85	4	225*10*10
	-	S355J2	7.85	1	450*10*15
	-	S355J2	7.85	1	450*10*15
	-	S355J2	7.85	1	450*10*15
	-	S355J2	7.85	2	600*10*20
	-	S355J2	7.85	1	300*10*10
	-	S355J2	7.85	2	100*5*10
	-	S355J2	7.85	1	100*5*10
	-	S355J2	7.85	2	900*15*20
	-	S355J2	7.85	1	600*10*20
	-	S355J2	7.85	1	100*5*10
	-	S355J2	7.85	1	300*10*10
	-	S355J2	7.85	1	300*10*10

Gantry Section	Description	Steel Grade	Volume	Length	Weight
Trestle (T1)	Square Hollow Section	S355J2H	101992	335.5	**1601.2**
	-	S355J2H	39545.6	185	**310.4**
	Rectangular Plate	S275J2G3	47250	-	**741.8**
	-	S275J2G3	24500	-	**384.6**
	Flat Plate	S275	108	3	**1.6**
	Rolled Steel Angle	S275	3996	185	**62.7**
	-	S275	1080	50	**8.4**
Trestle (T2)	Square Hollow Section	S355J2H	130872	430.5	**2054.6**
	-	S355J2H	39545.6	185	**310.4**
	Rectangular Plate	S275J2G3	47250	-	**741.8**
	-	S275J2G3	24500	-	**384.6**
	Flat Plate	S275	1080	3	**16.9**
	Rolled Steel Angle	S275	3996	185	**62.7**
	-	S275	1080	50	**8.4**
MS4 Frame	Square Hollow Section	S355J2H	30396	506.6	**238.6**
	-	S355J2H	30330	505.5	**238**
	-	S355J2H	21152.25	331.8	**498.1**
	-	S355J2H	5186.08	181	**162.8**
	-	S355J2H	1679.03	58.6	**13.1**
	-	S355J2H	1902.52	66.4	**14.9**
	-	S355J2H	2126.01	74.2	**16.6**
	Rectangular Plate	S275J2	214.5	-	**1.6**
	-	S275J2	98.3	-	**1.5**
	Flat Plate	S275	15	5	**0.2**
	Rectangular Plate	S355J2	219.04	-	**6.8**
	-	S355J2	331.11	-	**15.5**
	-	S355J2	609	-	**28.6**
	-	S355J2	625.8	-	**29.4**
	Neoprene Strip	N/A	1160	29	**1.3**
	20 Sq Bar	S275	16	80	**1.5**
MS4 Frame 2	Square Hollow Section	S355J2H	30396	506.6	**238.6**
	-	S355J2H	30330	505.5	**238**
	-	S355J2H	21152.25	331.8	**498.1**
	-	S355J2H	5186.08	181	**162.8**
	-	S355J2H	1679.03	58.6	**13.1**
	-	S355J2H	1902.52	66.4	**14.9**
	-	S355J2H	2126.01	74.2	**16.6**
	Rectangular Plate	S275J2	214.5	-	**1.6**
	-	S275J2	98.3	-	**1.5**
	Flat Plate	S275	15	5	**0.2**
	Rectangular Plate	S355J2	219.04	-	**6.8**
	-	S355J2	331.11	-	**15.5**
	-	S355J2	609	-	**28.6**
	-	S355J2	625.8	-	**29.4**
	Neoprene Strip	N/A	-	29	**0**
	20 Sq Bar	S275	16	80	**1.5**
Main Truss	Square Hollow Section	S355J2H	328707.6	4325.1	**10321.4**
	-	S355J2H	4388.6	236.3	**137.8**
	-	S355J2H	4377.5	235.7	**2336.7**
	Rectangular Hollow Section	S355J2H	9430	205	**1332.4**
	-	S355J2H	10882.8	302.3	**1452.3**
	-	S355J2H	8323.2	231.2	**130.6**
	-	S355J2H	6560	205	**875.4**
	-	S355J2H	4381.2	305	**550.2**
	-	S355J2H	7911.36	301.5	**124.2**
	Rectangular Plate	S355J2	510	-	**56**
	Lintel	S355J2	3915	14.5	**245.8**
	-	S275	11700	225	**183.6**
	-	S275	11700	225	**183.6**
	-	S275	907.2	42	**28.4**
	Rectangular Plate	S355J2	346.8	-	**76.2**
	-	S275	173.4	-	**2.7**
	-	S275	2641.2	-	**20.7**
	-	S275	3596.4	-	**28.2**
	-	S355J2	1012.5	-	**31.7**
	-	S355J2	720	-	**22.6**
	-	S355J2	231	-	**7.2**
	-	S355J2	231	-	**7.2**
	Lintel	S275	450	4	**14.1**
	-	S275	328	41	**48.9**

Gantry Section	Description	Steel Grade	Volume	Length	Weight
Truss (cont..)	-	S275	160	20	**5**
	-	S275	1350.4	168.8	**21.2**
	Rectangular Hollow Section	S275J2H	90	32.4	**1.4**
	Flat Plate	S275	54	15	**0.8**
	Lintel	S275	56	7	**7.9**
	Rectangular Plate	S275	2700	-	**21.1**
	Lintel	S275	208	4	**6.5**
	-	S275	656.64	30.4	**5.1**
	-	S275	1099.44	50.9	**8.6**
	M8 Bolts *25	4.6	-	-	-
	Rectangular Hollow Section	S355J2	2070	230	**32.4**
	-	S355J2	180	20	**5.6**
	-	S355J2	855	95	**13.4**
Header Rail	Lintel	S355J2	54630	485.6	**428.8**
	-	S355J2	27596.2	245.3	**216.6**
	-	S355J2	53088.7	471.9	**416.7**
	-	S355J2	27596.2	245.3	**216.6**
Sign Post	Universal Beam	S355J2	40294.6	853.7	**1265.2**
	-	S355J2	39397.8	834.7	**927.8**
	Rectangular Plate	S355J2	1372.1	-	**75.3**
	-	S355J2	1433.1	-	**78.7**
	-	S355J2	359.1	247.5	**19.7**
	-	S355J2	308.8	185	**2.4**
Gantry End 1	Rectangular Plate	S275J2G3	47250	-	**370.9**
	-	S275J2G3	24500	-	**192.3**
	Square Hollow Section	S355J2H	75240	-	**590.6**
	-	S355J2H	39545.6	247.5	**310.4**
	Rectangular Plate	S275J2G3	18000	185	141.3
Gantry End 2	Rectangular Plate	S275J2G3	47250	-	**370.9**
	-	S275J2G3	24500	157.4	**192.3**
	Square Hollow Section	S355J2H	75240	30	**590.6**
	-	S355J2H	39545.6	78	**310.4**
	Rectangular Plate	S275J2G3	18000	156	141.3
AMI Fr HS*2	Square Hollow Section	S355J2H	2923.2	157.4	**45.8**
	-	S355J2H	557.1	30	**8.7**
	-	S355J2H	1448.6	78	**22.7**
	-	S355J2H	2897.2	156	**45.4**
AMI F R L*6	Square Hollow Section	S355J2H	2923.2	7.5	**137.6**
	-	S355J2H	557.1	10	**26.2**
	-	S355J2H	1448.6	52	**68.2**
	-	S355J2H	2897.2	20	**136.4**
AMI 'Y' Frm*8	Flat Plate	S275	33.75	157	**2.1**
	-	S275J2G3	80	7.5	**5**
	Square Hollow Section	S355J2H	861.1	15	**54**
	Flat Plate	S275	160	75	**10**
	Square Hollow Section	S355J2H	2599.9	-	**163.2**
	Flat Plate	S275	33.75	-	**2.1**
	Flat Plate	S275	235	247.5	**14.7**
	Flat Plate	S275	360	185	**22.6**
Cable Tray	Medium Flange	S355J2	3150	140	**24.7**
	-	S355J2	135000	2000	**1059.7**
	-	S355J2	15862	235	**124.5**
	-	S355J2	114750	1700	**900.7**
	-	S355J2	28200	235	**221.3**
	-	S355J2	6150	205	**48.2**
	-	S355J2	8200	1640	**64.3**
	-	S355J2	975	195	**7.6**
	-	S355J2	81000	300	**635.8**
	-	S355J2	33600	280	**263.7**
	-	S355J2	618.75	123.75	**4.8**
	-	S355J2	7425	247.5	**58.2**
	-	S355J2	3712.5	123.75	**29.1**

Gantry Section	Description	Steel Grade	Drilling cm^3 (D*T)	QTY	Void
Trestle (T1)	Square Hollow Section	S355J2H	-	-	
	-	S355J2H	-	-	
	Rectangular Plate	S275J2G3	40 (4.0*7.5)* 2	8	480
	-	S275J2G3	39 (3.9*5.0)* 2	14	546
	Flat Plate	S275	12 (1.2*0.6)* 2	1	1.44
	Rolled Steel Angle	S275	14 (1.4*0.6)* 2	5	8.4
	-	S275	14 (1.4*0.6)	3	2.52
Trestle (T2)	Square Hollow Section	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Plate	S275J2G3	40 (4.0*7.5)* 2	8	480
	-	S275J2G3	39 (3.9*5.0)* 2	14	546
	Flat Plate	S275	12 (1.2*0.6)* 2	1	1.44
	Rolled Steel Angle	S275	14 (1.4*0.6)* 2	5	8.4
	-	S275	14 (1.4*0.6)	3	2.52
MS4 Frame	Square Hollow Section	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Plate	S275J2	8 (0.8*0.6)	4	1.92
	-	S275J2	-	-	-
	Flat Plate	S275	12 (1.2*0.6) * 2	1	1.4
	Rectangular Plate	S355J2	-	-	-
	-	S355J2	-	-	-
	-	S355J2	18 (1.8*1.0) * 6	4	43.2
	-	S355J2	18 (1.8*1.0) * 6	4	43.2
	Neoprene Strip	N/A	-	-	-
	20 Sq Bar	S275	-	-	-
MS4 Frame 2	Square Hollow Section	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Plate	S275J2	8 (0.8*0.6)	4	1.9
	-	S275J2	-	-	-
	Flat Plate	S275	12 (1.2*0.6) * 2	1	1.4
	Rectangular Plate	S355J2	-	-	-
	-	S355J2	-	-	-
	-	S355J2	18 (1.8*1.0) * 6	4	43.2
	-	S355J2	18 (1.8*1.0) * 6	4	43.2
	Neoprene Strip	N/A	-	12	-
	20 Sq Bar	S275	-	12	-
Main Truss	Square Hollow Section	S355J2H	5 (0.5*1.0) * 4	3	6
	-	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Hollow Section	S355J2H	-	-	-
	-	S355J2H	18 (1.8*1.0) * 17	4	122.4
	-	S355J2H	18 (1.8*1.0) * 2	2	7.2
	-	S355J2H	-	-	-
	-	S355J2H	8*12 (0.8*1.2*0.8) * 16	4	49.1
	-	S355J2H	-	-	-
	Rectangular Plate	S355J2	-	-	-
	Lintel	S355J2	18 (1.8*1.2) * 8	4	69.1
	-	S275	14 (1.4*0.8) * 2	4	8.9
	-	S275	14 (1.4*0.8) * 2	6	13.4
	-	S275	14 (1.8*0.6) * 4	4	17.2
	Rectangular Plate	S355J2	45 (4.5*1.2)*28|22(2.2*1.2) * 28	1+1	255.3
	-	S275	50 (5*0.4)*2|(0.7*1.1*0.4) * 2	1+2	73.2
	-	S275	14 (1.4*0.6)|12 (1.2*0.6)	10+4	11.28
	-	S275	14 (1.4*0.6)	12	10.08
	-	S355J2	-	-	-
	-	S355J2	67 (6.7*2.0)* 4	1	53.6
	-	S355J2	-	-	-
	-	S355J2	10 (1.0*2.0)* 4	1	8
	Lintel	S275	14 (1.4*1.0)* 4	1	5.6
	-	S275	12*30 (1.2*3.0*0.5)* 19	3	34.2

Gantry Section	Description	Steel Grade	Drilling	QTY	Void
Truss (cont..)	-	S275	12*30 (1.2*3.0*0.5)*4	2	14.4
	-	S275	12*30 (1.2*3.0*0.5)*2	3	10.8
	Rectangular Hollow Section	S275J2H	-	-	-
	Flat Plate	S275	12*30 (1.2*3.0*0.6)*2	2	8.64
	Lintel	S275	12 (1.2*0.5)*18	2	21.6
	Rectangular Plate	S275	9 (0.9*0.6)	4	2.16
	Lintel	S275	-	-	-
	-	S275	12 (1.2*0.6)	2	1.44
	-	S275	12 (1.2*0.6)	2	1.44
	M8 Bolts *25	4.6	-	-	-
	Rectangular Hollow Section	S355J2	-	-	-
	-	S355J2	-	-	-
	-	S355J2	-	-	-
Header Rail	Lintel	S355J2	18 (1.8*1.0)	10	18
	-	S355J2	18 (1.8*1.0)	6	10.8
	-	S355J2	18 (1.8*1.0)	8	14.4
	-	S355J2	18 (1.8*1.0)	6	10.8
Sign Post	Universal Beam	S355J2	-	-	-
	-	S355J2	-	-	-
	Rectangular Plate	S355J2	22 (2.2*3.0)*7|45 (4.5*3.0)*7	1+1	140.7
	-	S355J2	22 (2.2*3.0)*7|45 (4.5*3.0)*7	1+1	140.7
	-	S355J2	18 (1.8*1.0)*7	4	50.4
	-	S355J2	18 (1.8*1.0)	2	3.6
Gantry End 1	Rectangular Plate	S275J2G3	40 (4.0*7.5)	8	240
	-	S275J2G3	39 (3.9*5.0)	14	273
	Square Hollow Section	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Plate	S275J2G3	-	-	-
Gantry End 2	Rectangular Plate	S275J2G3	40 (4.0*7.5)	8	240
	-	S275J2G3	39 (3.9*5.0)	14	273
	Square Hollow Section	S355J2H	-	-	-
	-	S355J2H	-	-	-
	Rectangular Plate	S275J2G3	-	-	-
AMI Fr HS*2	Square Hollow Section	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
AMI F R L*6	Square Hollow Section	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
	-	S355J2H	No Data	-	-
AMI 'Y' Frm*8	Flat Plate	S275	No Data	-	-
	-	S275J2G3	No Data	-	-
	Square Hollow Section	S355J2H	No Data	-	-
	Flat Plate	S275	No Data	-	-
	Square Hollow Section	S355J2H	No Data	-	-
	Flat Plate	S275	No Data	-	-
	Flat Plate	S275	No Data	-	-
	Flat Plate	S275	No Data	-	-
Cable Tray	Medium Flange	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-
	-	S355J2	No Data	-	-

Gantry Section	Description	MAG Welding	Scrap	Final Weight
Trestle (T1)	Square Hollow Section	304 (1600 - 1296)		**1601.2**
	-	427.52 (1225 - 1011.24*2)		**310.4**
	Rectangular Plate	-	3.768	**738**
	-	-	4.2861	**380.3**
	Flat Plate	3.6 (6*0.6)	0.011304	**1.6**
	Rolled Steel Angle	43.2 (6*6*0.6)	0.06594	**62.6**
	-	800 (4*4*50)	0.019782	**8.4**
Trestle (T2)	Square Hollow Section	304 (1600 - 1296)		**2054.6**
	-	427.52 (1225 - 1011.24*2)		**310.4**
	Rectangular Plate	-	3.768	**738**
	-	-	4.2861	**380.3**
	Flat Plate	3.6 (6*0.6)	0.011304	**16.9**
	Rolled Steel Angle	43.2 (6*6*0.6)	0.06594	**62.6**
	-	800 (4*4*50)	0.019782	**8.4**
MS4 Frame	Square Hollow Section	-		**238.6**
	-	272.16 (12*12*0.63*3)		**238**
	-	63.75 (196-132.25)		**498.1**
	-	57.3048 (144-115.3476*2)		**162.8**
	-	57.3048 (144- 115.3476*2)		**13.1**
	-	57.3048 (144- 115.3476*2)		**14.9**
	-	57.3048 (144- 115.3476*2)		**16.6**
	Rectangular Plate	63.75 (196-132.25)	0.015072	**1.6**
	-	63.75 (196-132.25)		**1.5**
	Flat Plate	3 (5.0*0.6*2)	0.011304	**0.2**
	Rectangular Plate	240 (256-196)		**6.8**
	-	40 (11.7+28.3)		**15.5**
	-	1008 (21*16*3)	0.33912	**28.3**
	-	1008 (21*16*3)	0.33912	**29.1**
	Neoprene Strip	-		**1.3**
	20 Sq Bar	-		**1.5**
MS4 Frame 2	Square Hollow Section	-		**238.6**
	-	272.16 (12*12*0.63*3)		**238**
	-	63.75 (196-132.25)		**498.1**
	-	57.3048 (144-115.3476*2)		**162.8**
	-	57.3048 (144- 115.3476*2)		**13.1**
	-	57.3048 (144- 115.3476*2)		**14.9**
	-	57.3048 (144- 115.3476*2)		**16.6**
	Rectangular Plate	63.75 (196-132.25)	0.015072	**1.6**
	-	63.75 (196-132.25)		**1.5**
	Flat Plate	3 (5.0*0.6*2)	0.011304	**0.2**
	Rectangular Plate	240 (256-196)		**6.8**
	-	40 (11.7+28.3)		**15.5**
	-	1008 (21*16*3)	0.33912	**28.3**
	-	1008 (21*16*3)	0.33912	**29.1**
	Neoprene Strip	-		**1.3**
	20 Sq Bar	-		**1.5**
Main Truss	Square Hollow Section	152 (400-324*2)	0.0471	**10321.3**
	-	18.5724 (64-45.4276*2)		**137.8**
	-	18.5724 (64-45.4276*2)		**2336.7**
	Rectangular Hollow Section	92 (150-104*2)		**1332.4**
	-	72 (96-60*2)	0.96084	**1451.3**
	-	72 (96-60*2)	0.05652	**130.6**
	-	64 (72-40*2)		**875.4**
	-	64 (72-40*2)	0.3858432	**549.8**
	-	64 (72-40*2)		**124.2**
	Rectangular Plate	255 (17*15)		**56**
	Lintel	18 (15*1.2)	0.542592	**245.3**
	-	130 (6.5*10*2)	0.070336	**183.6**
	-	130 (6.5*10*2)	0.105504	**183.5**
	-	36 (6*6)	0.135648	**28.3**
	Rectangular Plate	20.4 (17*1.2)	2.004576	**74.2**
	-	4 (10*0.4)	0.5749968	**2.1**
	-	-	0.088548	**20.6**
	-	-	0.079128	**28.1**
	-	450 (22.5*20)		**31.7**
	-	40 (20*2)	0.42076	**22.1**
	-	14 (7*2)|33 (16.5*2)		**7.2**
	-	14 (7*2)|33 (16.5*2)	0.0628	**7.1**
	Lintel	15 (15*1)	0.04396	**14**
	-	164 (4*41)	0.26847	**48.6**

Gantry Section	Description	MAG Welding	Scrap	Final Weight
Truss (cont..)	-	80 (4*20)	0.11304	**4.9**
	-	40 (80*0.5)	0.08478	**21.1**
	Rectangular Hollow Section	18 (25-16*2)		**1.4**
	Flat Plate	-	0.067824	**0.7**
	Lintel	28 (7*4)	0.16956	**7.7**
	Rectangular Plate	36 (60*0.6)	0.016956	**21.1**
	Lintel	0.32 (0.8*0.4)		**6.5**
	-	48 (6*8)	0.011304	**5.1**
	-	48 (6*8)	0.011304	**8.6**
	M8 Bolts *25	-		-
	Rectangular Hollow Section	25 (5*5)		**32.4**
	-	25 (5*5)		**5.6**
	-	25 (5*5)		**13.4**
Header Rail	Lintel	-	0.1413	**428.7**
	-	-	0.08478	**216.5**
	-	-	0.11304	**416.6**
	-	-	0.08478	**216.5**
Sign Post	Universal Beam	365 (25*14.6)		**1265.2**
	-	365 (25*14.6)		**927.8**
	Rectangular Plate	51 (17*3)	1.104495	**74.2**
	-	51 (17*3)	1.104495	**77.6**
	-	-	0.39564	**19.3**
	-	26 (13.2*1*2)	0.02826	**2.3**
Gantry End 1	Rectangular Plate	-	1.884	**369**
	-	-	2.14305	**190.1**
	Square Hollow Section	304 (1600 - 1296)		**590.6**
	-	427.52 (1225 - 1011.24*2)		**310.4**
	Rectangular Plate	-		141.3
Gantry End 2	Rectangular Plate	-	1.884	**369**
	-	-	2.14305	**190.1**
	Square Hollow Section	304 (1600 - 1296)		**590.6**
	-	427.52 (1225 - 1011.24*2)		**310.4**
	Rectangular Plate	-		**141.3**
AMI Fr HS*2	Square Hollow Section	18.5724 (64-45.4276*2)		**45.8**
	-	18.5724 (64-45.4276*2)		**8.7**
	-	18.5724 (64-45.4276*2)		**22.7**
	-	18.5724 (64-45.4276*2)		**45.4**
AMI F R L*6	Square Hollow Section	18.5724 (64-45.4276*2)		**137.6**
	-	18.5724 (64-45.4276*2)		**26.2**
	-	18.5724 (64-45.4276*2)		**68.2**
	-	18.5724 (64-45.4276*2)		**136.4**
AMI 'Y' Frm*8	Flat Plate	-		-
	-	-		-
	Square Hollow Section	-		-
	Flat Plate	-		-
	Square Hollow Section	-		-
	Flat Plate	-		-
	Flat Plate	-		-
	Flat Plate	-		-
Cable Tray	Medium Flange	-		**24.7**
	-	-		**1059.7**
	-	-		**124.5**
	-	-		**900.7**
	-	-		**221.3**
	-	-		**48.2**
	-	-		**64.3**
	-	-		**7.6**
	-	-		**635.8**
	-	-		**263.7**
	-	-		**4.8**
	-	-		**58.2**
	-	-		**29.1**

Gantry Section	Description	Steel Bolts	Density (g/cm^3)	Bolt QTY	Steel Bolt Weight
Trestle (T1)	Square Hollow Section	-	7.85	-	
	-	-	7.85	-	
	Rectangular Plate	M36 H.D.	7.85	8	96 (8*12)
	-	M36 HSFG	7.85	14	23.8 (14*8)
	Flat Plate	-	7.85	1	1 (1*1)
	Rolled Steel Angle	-	7.85	5	6 (5*1.2)
	-	-	7.85	3	3.6 (3*1.2)
Trestle (T2)	Square Hollow Section	-	7.85	-	
	-	-	7.85	-	
	Rectangular Plate	M36 H.D.	7.85	8	96 (8*12)
	-	M36 HSFG	7.85	14	23.8 (14*1.7)
	Flat Plate	Standard	7.85	1	0.1 (1*0.1)
	Rolled Steel Angle	Standard	7.85	5	0.5 (5*0.1)
	-	Standard	7.85	3	0.3 (3*0.1)
MS4 Frame	Square Hollow Section	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	Rectangular Plate	-	7.85	4	0.04 (4*0.01)
	-	-	7.85	-	-
	Flat Plate	-	7.85	1	0.01 (1*0.01)
	Rectangular Plate	-	7.85	-	-
	-	-	7.85	-	-
	-	4x M16 Bolt	7.85	4	1.2 (4*0.3)
	-	Wash and nut	7.85	4	1.2 (4*0.3)
	Neoprene Strip	-	7.85	-	-
	20 Sq Bar	-	7.85	-	-
MS4 Frame 2	Square Hollow Section	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	-	-	7.85	-	-
	Rectangular Plate	-	7.85	4	0.04 (4*0.01)
	-	-	7.85	-	-
	Flat Plate	-	7.85	1	0.01 (1*0.01)
	Rectangular Plate	-	7.85	-	-
	-	-	7.85	-	-
	-	4x M16 Bolt	7.85	4	1.2 (4*0.3)
	-	Wash and nut	7.85	4	1.2 (4*0.3)
	Neoprene Strip	-	7.85	-	-
	20 Sq Bar	-	7.85	-	-
Main Truss	Square Hollow Section	No data	7.85	3	0.3 (3*0.1)
	-	No data	7.85	-	-
	-	No data	7.85	-	-
	Rectangular Hollow Section	No data	7.85	-	-
	-	No data	7.85	4	1.2*(4*0.03)
	-	No data	7.85	2	0.06 (2*0.06)
	-	No data	7.85	-	-
	-	No data	7.85	4	0.08 (4*0.02)
	-	No data	7.85	-	-
	Rectangular Plate	No data	7.85	-	-
	Lintel	No data	7.85	4	0.4 (4*0.1)
	-	No data	7.85	4	0.4 (4*0.1)
	-	No data	7.85	6	0.6 (6*0.1)
	-	No data	7.85	4	0.4 (4*0.1)
	Rectangular Plate	No data	7.85	1+1	1 (1*0.1)
	-	No data	7.85	1+2	1 (1*0.2)
	-	No data	7.85	10+4	1 (10*0.1)
	-	No data	7.85	12	1.2 (12*0.1)
	-	No data	7.85	-	-
	-	No data	7.85	1	10 (1*10)
	-	No data	7.85	-	-
	-	No data	7.85	1	0.2 (1*0.2)
	Lintel	No data	7.85	1	0.2 (1*0.2)
	-	No data	7.85	3	0.06 (3*0.02

Gantry Section	Description	Steel Bolt Weight	Density (g/cm^3)	Bolt QTY	Steel Bolts
Truss (cont..)	-	No data	7.85	2	0.04 (2*0.02)
	-	No data	7.85	3	0.06 (2*0.03)
	Rectangular Hollow Section	No data	7.85	-	-
	Flat Plate	No data	7.85	2	0.04 (2*0.02)
	Lintel	No data	7.85	2	0.04 (2*0.02)
	Rectangular Plate	No data	7.85	4	0.08 (4*0.02)
	Lintel	No data	7.85	-	-
	-	No data	7.85	2	0.04 (2*0.02)
	-	No data	7.85	2	0.04 (2*0.02)
	M8 Bolts *25	No data	7.85	4	20 (4*5)
	Rectangular Hollow Section	No data	7.85	-	-
	-	No data	7.85	-	-
	-	No data	7.85	-	-
Header Rail	Lintel	No data	7.85	10	2 (10*0.2)
	-	No data	7.85	6	1.2 (6*0.2)
	-	No data	7.85	8	1.6 (8*0.2)
	-	No data	7.85	6	1.2 (6*0.2)
Sign Post	Universal Beam	No data	7.85	-	-
	-	No data	7.85	-	-
	Rectangular Plate	No data	7.85	1+1	1.5 (1*0.5*1)
	-	No data	7.85	1+1	1.5 (1*0.5*1)
	-	No data	7.85	4	2 (4*0.5)
	-	No data	7.85	2	1 (2*0.5)
Gantry End 1	Rectangular Plate	No data	No data	No data	No data
	-	No data	No data	No data	No data
	Square Hollow Section	No data	No data	No data	No data
	-	No data	No data	No data	No data
	Rectangular Plate	No data	No data	No data	No data
Gantry End 2	Rectangular Plate	No data	No data	No data	No data
	-	No data	No data	No data	No data
	Square Hollow Section	No data	No data	No data	No data
	-	No data	No data	No data	No data
	Rectangular Plate	No data	No data	No data	No data
AMI Fr HS*2	Square Hollow Section	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
AMI F R L*6	Square Hollow Section	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
AMI 'Y' Frm*8	Flat Plate	No data	No data	No data	No data
	-	No data	No data	No data	No data
	Square Hollow Section	No data	No data	No data	No data
	Flat Plate	No data	No data	No data	No data
	Square Hollow Section	No data	No data	No data	No data
	Flat Plate	No data	No data	No data	No data
	Flat Plate	No data	No data	No data	No data
	Flat Plate	No data	No data	No data	No data
Cable Tray	Medium Flange	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data
	-	No data	No data	No data	No data

Gantry Section	Description	Blasting (m^2)	Paint (1st + 2nd)	Paint (3rd + 4th)
Trestle (T1)	Square Hollow Section	400.3	53.3	228.7
	-	77.6	10.3	44.3
	Rectangular Plate	184.5	24.6	105.4
	-	95.0	12.6	54.3
	Flat Plate	0.4	0	0.2
	Rolled Steel Angle	15.6	2	8.9
	-	2.1	0.2	1.2
Trestle (T2)	Square Hollow Section	513.6	68.4	293.5
	-	77.6	10.3	44.3
	Rectangular Plate	184.5	24.6	105.4
	-	95	12.6	54.3
	Flat Plate	4.2	0.5	2.4
	Rolled Steel Angle	15.6	2	8.9
	-	2.1	0.2	1.2
MS4 Frame	Square Hollow Section	59.6	7.9	34
	-	59.5	7.9	34
	-	124.5	16.6	71
	-	40.7	5.4	23.2
	-	3.2	0.4	1.8
	-	3.7	0.4	2.1
	-	4.1	0.5	2.3
	Rectangular Plate	0.4	0	0.2
	-	0.3	0	0.2
	Flat Plate	0	0	0
	Rectangular Plate	1.7	0	0.9
	-	3.8	0	2.2
	-	7	0	4
	-	7.2	0	4.1
	Neoprene Strip	N/A	N/A	N/A
	20 Sq Bar	0.3	0	0.2
MS4 Frame 2	Square Hollow Section	59.6	7.9	34
	-	59.5	7.9	34
	-	124.5	16.6	71.1
	-	40.7	5.4	23.2
	-	3.2	0.4	1.8
	-	3.7	0.4	2.1
	-	4.1	0.5	2.3
	Rectangular Plate	0.4	0	0.2
	-	0.3	0	0.2
	Flat Plate	0	0	0
	Rectangular Plate	1.7	0.2	0.9
	-	3.8	0.5	2.2
	-	7	0.9	4
	-	7.2	0.9	4.1
	Neoprene Strip	N/A	N/A	N/A
	20 Sq Bar	0.3	0	0.2
Main Truss	Square Hollow Section	2580.3	172	1474.4
	-	34.4	2.2	19.6
	-	584.1	38.9	333.8
	Rectangular Hollow Section	333.1	22.2	190.3
	-	362.8	24.1	207.3
	-	32.6	2.1	18.6
	-	218.8	14.5	125
	-	137.4	9.1	78.5
	-	31	2	17.7
	Rectangular Plate	14	0.9	8
	Lintel	61.3	4	35
	-	45.9	3	26.2
	-	45.8	3	26.2
	-	7	0.4	4
	Rectangular Plate	18.5	1.2	10.6
	-	0.5	0	0.3
	-	5.1	0.3	2.9
	-	7	0.4	4
	-	7.9	0.5	4.5
	-	5.5	0.3	3.1
	-	1.8	0.1	1
	-	1.7	0.1	1
	Lintel	3.5	0.2	2
	-	12.1	0.8	6.9

Gantry Section	Description	Blasting (m^2)	Paint (1st + 2nd)	Paint (3rd + 4th)
Truss (cont..)	-	1.2	0	0.7
	-	5.2	0.3	3
	Rectangular Hollow Section	0.3	0	0.2
	Flat Plate	0.1	0.	0.1
	Lintel	1.9	0.1	1.1
	Rectangular Plate	5.2	0.3	3
	Lintel	1.6	0.1	0.9
	-	1.2	0	0.7
	-	2.1	0	1.2
	M8 Bolts *25	-	-	-
	Rectangular Hollow Section	8.1	0	4.6
	-	1.4	0	0.8
	-	3.3	0	1.9
Header Rail	Lintel	107.1	7.1	61.2
	-	54.1	3.6	30.9
	-	104.1	6.9	59.5
	-	54.1	3.6	30.9
Sign Post	Universal Beam	316.3	21	180.7
	-	231.9	15.4	132.5
	Rectangular Plate	18.5	1.2	10.6
	-	19.4	1.2	11
	-	4.8	0.3	2.7
	-	0.5	0	0
Gantry End 1	Rectangular Plate	No data	No data	No data
	-	No data	No data	No data
	Square Hollow Section	No data	No data	No data
	-	No data	No data	No data
	Rectangular Plate	No data	No data	No data
Gantry End 2	Rectangular Plate	No data	No data	No data
	-	No data	No data	No data
	Square Hollow Section	No data	No data	No data
	-	No data	No data	No data
	Rectangular Plate	No data	No data	No data
AMI Fr HS*2	Square Hollow Section	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
AMI F R L*6	Square Hollow Section	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
AMI 'Y' Frm*8	Flat Plate	No data	No data	No data
	-	No data	No data	No data
	Square Hollow Section	No data	No data	No data
	Flat Plate	No data	No data	No data
	Square Hollow Section	No data	No data	No data
	Flat Plate	No data	No data	No data
	Flat Plate	No data	No data	No data
	Flat Plate	No data	No data	No data
Cable Tray	Medium Flange	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data
	-	No data	No data	No data

Standard Road-side Equipment for M42 ATM Junction 3a to 7

ITS Component	Sub-Component	Peak (VA)	P.Factor	Actual Power (watts)
Equipment Cabinet CECLB	Internal Lighting	80	0.9	72
-	Heating and Cooling	2200	0.9	1980
-	Maint. Equipment	690	0.9	621
-	Roadside Equipment	480	0.9	432
NRTS Load (Rectifiers -Backup)	-	2500	0.9	2250
Message Sign MK4 (x2)	-	2430	0.9	2187
Advanced Motorway Indicator (x8)	-	1480	0.9	1332
Equipment Cabinet CECR	Internal Lighting	30	0.9	27
-	Heating and Cooling	800	0.9	720
-	Maint. Equipment	690	0.9	621
-	Roadside Equipment	280	0.9	252
-	***Total***	**11,660**	-	**10,494**

Enforcement Locations for M42 (Inc. Standard Equipment)

ITS Component	Sub-Component	Peak (VA)	P.Factor	Actual Power (watts)
CECEB (replaces CECLB)	Heating and Cooling	100	0.9	90
-	HADECS Controllers	230	0.9	207
-	Network Interface Unit	58	0.9	52.2
HADECS Flash Units (x2)	-	2300	0.9	2070
HADECS Camera Heads (x2)	-	874	0.9	786.6
	Enforced Total	**3562**	-	**3205.8**
	Inc. Standard Total	**15222**	-	**13,699.8**

Additional Equipment for M42

ITS Component	Sub-Component	Peak (VA)	P.Factor	Actual Power (watts)
Fixed CCTV (x2/1 Per CEC)	-	1280	0.9	1152
ADS Lighting	-	2000	0.9	1800
	Total	**3280**	-	**2952**

Energy Output for Standard Road-side Equipment: M42 ATM Junction 3a to 7

ITS Component	Sub-Component	Daily (kW/h)	Annual (kW/h	Lifespan (kW/h)
Equipment Cabinet CECLB	Internal Lighting	1.7	630.7	9460.8
-	Heating and Cooling	47.5	17,344.8	26,0172
-	Maint. Equipment	14.9	5439.9	81,599.4
-	Roadside Equipment	10.3	3784.3	56,764.8
NRTS Load (Rectifiers -Backup)	-	54	19710	295,650
Message Sign MK4 (x2)	-	13.1	4789.5	71,842.9
Advanced Motorway Indicator (x8)	-	7.9	2917	43,756.2
Equipment Cabinet CECR	Internal Lighting	0.6	236.5	3547.8
-	Heating and Cooling	17.2	6307.2	94,608
-	Maint. Equipment	14.9	5439.9	81,599.4
-	Roadside Equipment	6	2207.5	33,112.8
-	***Total***	**188.5**	**68,807.6**	**1,032,114.1**

Energy Output for Enforcement Locations: M42 (Inc. Standard Equipment)

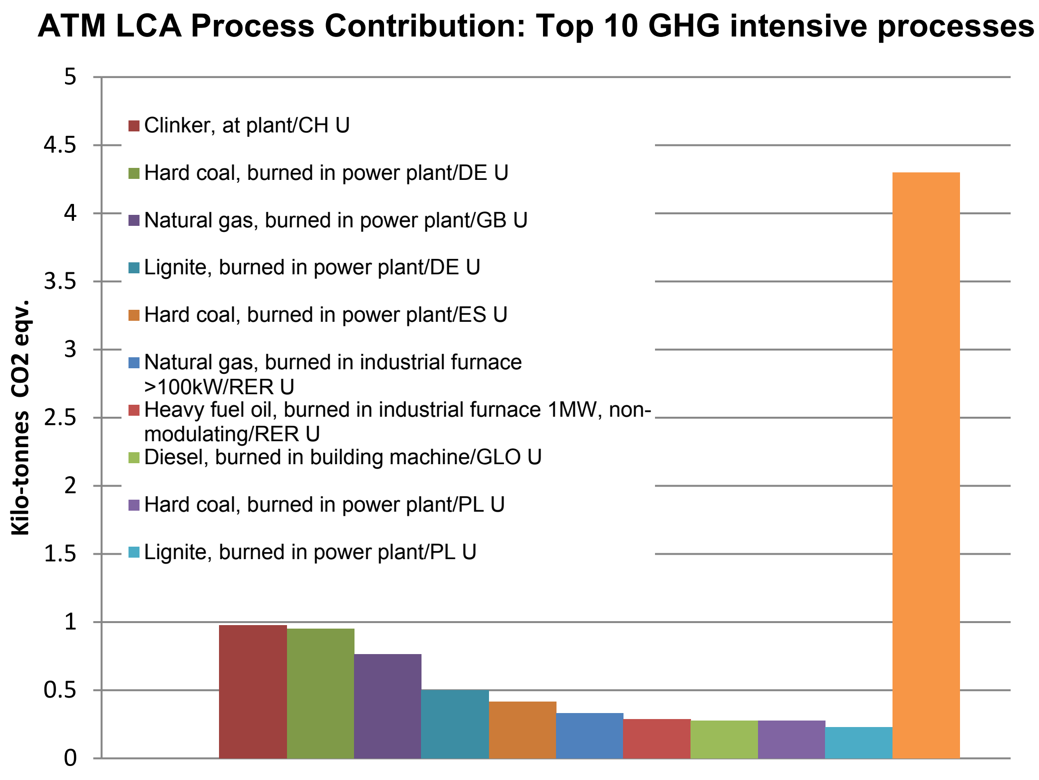
ITS Component	Sub-Component	Daily (kW/h)	Annual (kW/h	Lifespan (kW/h)
CECEB (replaces CECLB)	Heating and Cooling	2.1	788.4	11,826
-	HADECS Controllers	4.9	1813.3	27,199.8
-	Network Interface Unit	1.2	457.2	6859
HADECS Flash Units (x2)	-	49.6	18,133.2	271,998
HADECS Camera Heads (x2)	-	18.8	6890.6	103,359.2
	Enforced Total	**76.9**	**28,082.8**	**421,242.1**
	Inc. Standard Total	**265.4**	**96,890.4**	**1,453,356.2**

Energy Output for Additional Equipment: M42

ITS Component	Sub-Component	Daily (kW/h)	Annual (kW/h	Lifespan (kW/h)
Fixed CCTV (x2/1 Per CEC)	-	27.6	10,091.5	151,372.8
ADS Lighting	-	21.6	7884	118,260
-	***Total***	**49.2**	**17,975.5**	**269,632.8**

Max Load Totals:	**Peak (VA) = 18502**	**Actual Power (kW/h) = 16651.8**	**Daily (kW/h) = 314.7**	**Annual (kW/h) = 114,865.9**	**Lifespan (kW/h) = 2,144,231.1**

Appendix B: Full ATM Lifecycle Results for Road-side Infrastructure



Process Contribution per km up to 2020	500m Gantry Spacing (Kg CO_2 eqv.)	800m Gantry Spacing (Kg CO_2 eqv.)
Clinker, at plant/CH U	977,944.5	611,215.3
Hard coal, burned in power plant/DE U	949,799.9	593,624.9
Natural gas, burned in power plant/GB U	760,993	475,620.6
Lignite, burned in power plant/DE U	501,140.5	313,212.8
Hard coal, burned in power plant/ES U	416,629.3	260,393.36
Natural gas, burned in industrial furnace >100kW/RER U	330,537.5	206,585.9
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	285,939.4	178,712.1
Diesel, burned in building machine/GLO U	276,714.5	172,946.6
Hard coal, burned in power plant/PL U	274,954.4	171,846.5
Lignite, burned in power plant/PL U	228,525.7	142,828.5
Remaining processes	4,300,185.8	2,687,616.1

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Treatment, potato starch production effluent, to wastewater treatment, class 2/CH U	0.10	0.07
Uranium, enriched 3.8%, at TENEX enrichment plant/RU U	0.11	0.07
Soap, at plant/RER U	0.12	0.07
Treatment, PV cell production effluent, to wastewater treatment, class 3/CH U	0.12	0.08
Propane/ butane, at refinery/RER U	0.12	0.08
Uranium, enriched 4.2%, at URENCO enrichment plant/RER U	0.13	0.08
Treatment, plywood production effluent, to wastewater treatment, class 3/CH U	0.13	0.08
Electricity, medium voltage, at grid/ES U	0.14	0.09
Pentane, at plant/RER U	0.14	0.09
Acetic anhydride from ketene, at plant/RER U	0.15	0.09
Sodium perborate, tetrahydrate, powder, at plant/RER S	0.15	0.09
Green manure IP, until January/CH U	0.16	0.10
Treatment, concrete production effluent, to wastewater treatment, class 3/CH U	0.16	0.10
Disposal, asphalt, 0.1% water, to sanitary landfill/CH U	0.16	0.10
Disposal, polyvinylfluoride, 0.2% water, to municipal incineration/CH U	0.16	0.10
Rape seed IP, at farm/CH U	0.17	0.11
Ethylenediamine, at plant/RER U	0.17	0.11
Vinyl fluoride, at plant/US U	0.17	0.11
1,1-difluoroethane, HFC-152a, at plant/US U	0.17	0.11
Magnesium-alloy, AZ91, diecasting, at plant/RER U	0.18	0.11
Crude oil, production RLA, at long distance transport/RER U	0.18	0.11
Treatment, glass production effluent, to wastewater treatment, class 2/CH U	0.19	0.12
Crude oil, production RME, at long distance transport/CH U	0.21	0.13
Palm oil, at oil mill/MY U	0.22	0.14
Potato haulm cutting/CH U	0.22	0.14
Electricity, low voltage, at grid/CH U	0.22	0.14
Petrol, unleaded, at refinery/RER U	0.22	0.14
Mulching/CH U	0.26	0.16
Operation, lorry 20-28t, empty, fleet average/CH U	0.26	0.16
Glass tube, borosilicate, at plant/DE U	0.28	0.17
Electricity, medium voltage, production CH, at grid/CH U	0.28	0.18
Natural gas, burned in boiler atm. low-NOx condensing non-modulating <100kW/RER U	0.30	0.19
Tillage, hoeing and earthing-up, potatoes/CH U	0.33	0.21
Protein peas, IP, at farm/CH U	0.34	0.21
Electricity, hydropower, at pumped storage power plant/SE U	0.34	0.22
DAS-1, fluorescent whitening agent triazinylaminostilben type, at plant/RER U	0.35	0.22
Solid manure loading and spreading, by hydraulic loader and spreader/CH U	0.37	0.23
Sowing/CH U	0.38	0.24
Penta-erythritol, at plant/RER U	0.38	0.24
Sodium dithionite, anhydrous, at plant/RER U	0.39	0.24
Hexamethyldisilazane, at plant/GLO U	0.40	0.25
Potato planting/CH U	0.41	0.26
Electricity, medium voltage, at grid/IT U	0.42	0.27
Uranium, enriched 3.9%, at TENEX enrichment plant/RU U	0.47	0.29
Natural gas, burned in gas turbine/DE U	0.47	0.29
Electricity, high voltage, production CH, at grid/CH U	0.51	0.32
Crude oil, production NG, at long distance transport/RER U	0.53	0.33
Transport, tractor and trailer/CH U	0.54	0.34
Uranium, enriched 4.0%, at TENEX enrichment plant/RU U	0.56	0.35

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Kerosene, at refinery/RER U	0.56	0.35
Toluene diisocyanate, at plant/RER U	0.61	0.38
Application of plant protection products, by field sprayer/CH U	0.64	0.40
Tillage, harrowing, by spring tine harrow/CH U	0.64	0.40
Hexafluorethane, at plant/GLO U	0.65	0.41
Solid bleached board, SBB, at plant/RER U	0.67	0.42
Photovoltaic cell, single-Si, at plant/RER U	0.67	0.42
Propylene glycol, liquid, at plant/RER U	0.67	0.42
Fluorescent whitening agent distyrylbiphenyl type, at plant/RER U	0.73	0.46
Electricity, bagasse, sugarcane, at fermentation plant/BR U	0.73	0.46
Wood chips, from forest, hardwood, burned in furnace 50kW/CH U	0.79	0.49
Electricity, high voltage, at grid/SK U	0.79	0.49
Electricity, high voltage, at grid/HR U	0.79	0.49
Hard coal, at mine/CN U	0.81	0.51
Disposal, copper, 0% water, to municipal incineration/CH U	0.84	0.53
Combine harvesting/CH U	0.90	0.56
Disposal, cement-fibre slab, 0% water, to municipal incineration/CH U	0.91	0.57
Disposal, paper, 11.2% water, to sanitary landfill/CH U	0.94	0.59
Photovoltaic cell, multi-Si, at plant/RER U	0.97	0.61
Tillage, harrowing, by rotary harrow/CH U	1.06	0.66
Sulphate pulp, TCF bleached, at plant/RER U	1.07	0.67
Crude oil, production NG, at long distance transport/CH U	1.07	0.67
Ammonium carbonate, at plant/RER U	1.09	0.68
Disposal, polypropylene, 15.9% water, to municipal incineration/CH U	1.11	0.69
Refinery gas, at refinery/CH U	1.21	0.76
Wood chips, from industry, hardwood, burned in furnace 50kW/CH U	1.26	0.79
Disposal, aluminium, 0% water, to municipal incineration/CH U	1.26	0.79
Harvesting, by complete harvester, potatoes/CH U	1.30	0.81
Disposal, polystyrene, 0.2% water, to municipal incineration/CH U	1.30	0.82
Fertilising, by broadcaster/CH U	1.31	0.82
Dipropylene glycol monomethyl ether, at plant/RER U	1.33	0.83
Disposal, steel, 0% water, to municipal incineration/CH U	1.42	0.89
Uranium, enriched 4.0%, at URENCO enrichment plant/RER U	1.42	0.89
Paper, woodfree, uncoated, at integrated mill/RER U	1.44	0.90
Natural gas, high pressure, at consumer/SE U	1.46	0.91
Disposal, paint, 0% water, to municipal incineration/CH U	1.47	0.92
Phenolic resin, at plant/RER U	1.49	0.93
N-olefins, at plant/RER U	1.50	0.94
Disposal, residue from cooling tower, 30% water, to sanitary landfill/CH U	1.52	0.95
Operation, maintenance, airport/RER U	1.52	0.95
Polyphenylene sulfide, at plant/GLO U	1.53	0.95
Crude oil, production RAF, at long distance transport/CH U	1.58	0.99
Palladium, secondary, at refinery/RER U	1.59	0.99
Electricity, high voltage, at grid/PT U	1.66	1.04
Crude oil, production RAF, at long distance transport/RER U	1.67	1.04
Cyclohexanol, at plant/RER U	1.72	1.08
Trifluoromethane, at plant/GLO U	1.73	1.08
Electricity, hydropower, at pumped storage power plant/CH U	1.74	1.09
Bitumen, at refinery/RER U	1.79	1.12
Disposal, emulsion paint remains, 0% water, to hazardous waste incineration/CH U	1.81	1.13
Potato seed IP, at farm/CH U	1.82	1.14

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Uranium, enriched 3.9% at URENCO enrichment plant/RER U	1.82	1.14
Disposal, paint remains, 0% water, to hazardous waste incineration/CH U	1.82	1.14
Treatment, sewage, from residence, to wastewater treatment, class 2/CH U	1.82	1.14
Electricity, hydropower, at pumped storage power plant/AT U	1.86	1.16
Electricity, high voltage, at grid/CS U	1.87	1.17
Electricity, medium voltage, at grid/FR U	1.91	1.19
Propylene oxide, liquid, at plant/RER U	1.92	1.20
Electricity, hydropower, at pumped storage power plant/NO U	1.93	1.21
Tillage, ploughing/CH U	1.93	1.21
Zinc concentrate, at beneficiation/GLO U	1.93	1.21
Disposal, wood pole, chrome preserved, 20% water, to municipal incineration/CH U	1.98	1.24
Esters of versatic acid, at plant/RER S	2.09	1.30
Electricity, hydropower, at pumped storage power plant/SK U	2.16	1.35
Disposal, wood untreated, 20% water, to sanitary landfill/CH U	2.18	1.37
Hard coal, burned in power plant/CN U	2.21	1.38
Electricity, hydropower, at pumped storage power plant/HR U	2.24	1.40
Electricity, high voltage, at grid/NL U	2.26	1.41
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U	2.27	1.42
Electricity, medium voltage, at grid/BR U	2.28	1.43
Treatment, rainwater mineral oil storage, to wastewater treatment, class 2/CH U	2.38	1.49
Light fuel oil, at refinery/CH U	2.40	1.50
Lead concentrate, at beneficiation/GLO U	2.46	1.54
Uranium, enriched 3.0%, at USEC enrichment plant/US U	2.48	1.55
Phosphorus, white, liquid, at plant/RER U	2.49	1.56
Electricity, medium voltage, at grid/NL U	2.64	1.65
Crude oil, production GB, at long distance transport/RER U	2.78	1.74
Polyols, at plant/RER U	2.79	1.75
Silver, from combined gold-silver production, at refinery/PG U	2.83	1.77
Crude oil, production RU, at long distance transport/RER U	2.84	1.77
Secondary sulphur, at refinery/RER U	2.88	1.80
Electricity, hydropower, at pumped storage power plant/US U	2.95	1.84
Electricity, high voltage, at grid/GR U	2.97	1.85
Treatment, sewage, to wastewater treatment, class 3/CH U	2.99	1.87
Lignite briquette, burned in stove 5-15kW/RER U	3.03	1.89
Disposal, paper, 11.2% water, to municipal incineration/CH U	3.12	1.95
Electricity, medium voltage, at grid/GB U	3.20	2.00
Feldspar, at plant/RER S	3.21	2.01
Sulphate pulp, unbleached, at plant/RER U	3.24	2.02
Radioactive waste, in interim storage conditioning/CH U	3.27	2.04
Electricity, high voltage, SBB, at grid/CH U	3.27	2.05
Slurry spreading, by vacuum tanker/CH U	3.29	2.05
Propane/ butane, at refinery/CH U	3.30	2.06
Disposal, separator sludge, 90% water, to hazardous waste incineration/CH U	3.38	2.11
Methylene diphenyl diisocyanate, at plant/RER U	3.42	2.14
Crude oil, production NO, at long distance transport/RER U	3.47	2.17
Crude oil, at production offshore/NL U	3.51	2.19
Sodium dichromate, at plant/RER U	3.53	2.21
Treatment, sewage, to wastewater treatment, class 4/CH U	3.62	2.26
Cast iron, at plant/RER U	3.63	2.27
Heat, at cogen with biogas engine, allocation exergy/CH U	3.72	2.33
Corrugated board base paper, kraftliner, at plant/RER U	3.73	2.33

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Chlorine, gaseous, membrane cell, at plant/RER U	3.85	2.41
Crude oil, production RME, at long distance transport/RER U	3.90	2.44
Electricity, at cogen 6400kWth, wood, allocation exergy/CH U	3.95	2.47
Electricity, medium voltage, at grid/DE U	3.97	2.48
Disposal, anion exchange resin f. water, 50% water, to municipal incineration/CH U	4.03	2.52
Chlorine, gaseous, diaphragm cell, at plant/RER U	4.04	2.52
Corrugated board, mixed fibre, single wall, at plant/RER U	4.21	2.63
Disposal, glass, 0% water, to municipal incineration/CH U	4.22	2.64
Methyl ethyl ketone, at plant/RER U	4.34	2.71
Electricity, hydropower, at pumped storage power plant/FR U	4.44	2.78
Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH U	4.54	2.84
Electricity, hydropower, at pumped storage power plant/PT U	4.70	2.94
Sodium hydroxide, 50% in H2O, membrane cell, at plant/RER U	4.78	2.99
Molybdenum concentrate, main product/GLO U	4.89	3.06
Diesel, at refinery/CH U	5.03	3.15
Disposal, cation exchange resin f. water, 50% water, to municipal incineration/CH U	5.10	3.18
Sodium hydroxide, 50% in H2O, diaphragm cell, at plant/RER U	5.25	3.28
Electricity, hydropower, at pumped storage power plant/CS U	5.30	3.31
Silver, from combined metal production, at beneficiation/SE U	5.80	3.63
Steel, electric, chromium steel 18/8, at plant/RER U	5.88	3.68
Sugarcane, at farm/BR U	5.90	3.69
Electricity, medium voltage, at grid/SE U	5.97	3.73
Hot rolling, steel/RER U	6.11	3.82
Copper, secondary, at refinery/RER U	6.21	3.88
Methylchloride, at plant/WEU U	6.26	3.91
Lorry 16t/RER/I U	6.41	4.01
Crude oil, at production onshore/NL U	7.12	4.45
Urea, as N, at regional storehouse/RER U	7.21	4.50
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	7.23	4.52
Natural gas, high pressure, at consumer/CH U	7.25	4.53
Silver, from combined gold-silver production, at refinery/CL U	7.34	4.59
Phosphate rock, as P2O5, beneficiated, dry, at plant/MA U	7.53	4.70
Ethylene dichloride, at plant/RER U	7.55	4.72
Molybdenum concentrate, couple production Cu/GLO U	7.61	4.76
Electricity, high voltage, at grid/BE U	7.86	4.91
Silver, from combined gold-silver production, at refinery/PE U	8.35	5.22
Adipic acid, at plant/RER U	8.38	5.24
Electricity, hydropower, at pumped storage power plant/GR U	8.41	5.26
Paraffin, at plant/RER U	8.62	5.38
Corrugated board base paper, testliner, at plant/RER U	8.90	5.56
Electricity, hydropower, at pumped storage power plant/IT U	9.03	5.64
Sulphate pulp, ECF bleached, at plant/RER U	9.25	5.78
Electricity, medium voltage, at grid/NO U	9.44	5.90
Polystyrene, general purpose, GPPS, at plant/RER U	9.63	6.02
Paper, woodfree, coated, at integrated mill/RER U	9.73	6.08
Chlorine, gaseous, mercury cell, at plant/RER U	10.29	6.43
Electricity, high voltage, at grid/SE U	10.91	6.82
1-butanol, propylene hydroformylation, at plant/RER U	10.95	6.84
Glass fibre, at plant/RER U	11.51	7.19
Natural gas, high pressure, at consumer/FI U	11.68	7.30
Disposal, antifreezer liquid, 51.8% water, to hazardous waste incineration/CH U	11.79	7.37

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Sodium hydroxide, 50% in H2O, mercury cell, at plant/RER U	12.30	7.69
Natural gas, high pressure, at consumer/DK U	12.38	7.74
Operation, passenger car/CH U	12.82	8.01
Corrugated board base paper, wellenstoff, at plant/RER U	12.89	8.05
Electricity, high voltage, at grid/AT U	13.04	8.15
Disposal, emulsion paint, 0% water, to municipal incineration/CH U	13.40	8.38
Electricity, hydropower, at pumped storage power plant/LU U	13.45	8.40
Carboxymethyl cellulose, powder, at plant/RER S	13.58	8.48
Petroleum coke, at refinery/RER U	13.79	8.62
Disposal, wood untreated, 20% water, to municipal incineration/CH U	13.79	8.62
Palm fruit bunches, at farm/MY U	14.04	8.77
Green manure IP, until march/CH U	14.11	8.82
Polymethyl methacrylate, beads, at plant/RER U	14.67	9.17
Disposal, bitumen, 1.4% water, to sanitary landfill/CH U	14.83	9.27
Zeolite, powder, at plant/RER S	14.87	9.29
Bitumen, at refinery/CH U	14.92	9.33
Electricity, high voltage, at grid/PL U	15.00	9.37
Monoethanolamine, at plant/RER U	15.74	9.84
Electricity, low voltage, production UCTE, at grid/UCTE U	15.86	9.91
Potatoes IP, at farm/CH U	15.91	9.94
Wood chips, from industry, softwood, burned in furnace 300kW/CH U	16.18	10.11
Provision, stubbed land/MY U	16.70	10.44
Helium, at plant/GLO U	16.92	10.58
Electricity, high voltage, at grid/ES U	17.37	10.86
Crude oil, at production/NG U	17.41	10.88
Naphtha, at refinery/RER U	17.49	10.93
Electricity, high voltage, at grid/NO U	17.75	11.10
Soy beans IP, at farm/CH U	17.86	11.16
Heavy fuel oil, at refinery/CH U	17.87	11.17
Vinyl acetate, at plant/RER U	17.94	11.21
Refinery gas, at refinery/RER U	19.33	12.08
Transport, helicopter, LTO cycle/GLO U	19.70	12.32
Copper, primary, at refinery/ID U	19.82	12.39
Anthraquinone, at plant/RER S	20.79	12.99
Gold, at refinery/CA U	21.54	13.46
Electricity, hydropower, at pumped storage power plant/BE U	22.12	13.83
Transport, natural gas, offshore pipeline, long distance/DZ U	22.44	14.02
Peat, at mine/NORDEL U	22.75	14.22
Electricity, high voltage, at grid/BR U	22.76	14.23
Copper concentrate, at beneficiation/ID U	22.83	14.27
Electricity, hydropower, at reservoir power plant/CH U	23.69	14.80
Latex, at plant/RER S	24.25	15.15
Copper, blister-copper, at primary smelter/RER U	24.33	15.21
Natural gas, burned in cogen 1MWe lean burn/RER U	25.30	15.81
Ethyl benzene, at plant/RER U	25.40	15.87
Transport, helicopter/GLO U	28.83	18.02
Polystyrene, high impact, HIPS, at plant/RER U	29.50	18.44
Disposal, refinery sludge, 89.5% water, to hazardous waste incineration/CH U	30.10	18.81
Electricity, medium voltage, aluminium industry, at grid/GLO U	30.40	19.00
Disposal, plastic, industr. electronics, 15.3% water, to municipal incineration/CH U	31.35	19.59
Methyl ethyl ketone from butane, at plant/RER U	33.41	20.88

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Ethyl acetate from butane, at plant/RER U	33.41	20.88
Distribution network, electricity, low voltage/CH/I U	35.04	21.90
Gold, from combined metal production, at beneficiation/SE U	35.05	21.90
Electricity, high voltage, at grid/FR U	37.93	23.70
Natural gas, high pressure, at consumer/AT U	38.78	24.23
Methyl acrylate, at plant/GLO U	38.98	24.36
Disposal, plastic, consumer electronics, 15.3% water, to municipal incineration/CH U	40.10	25.06
Silicon carbide, at plant/RER U	40.20	25.12
Formaldehyde, production mix, at plant/RER U	40.46	25.29
Lignite, burned in power plant/FR U	41.69	26.05
Electricity, hydropower, at pumped storage power plant/PL U	42.51	26.57
Light fuel oil, at refinery/RER U	42.78	26.74
Disposal, bilge oil, 90% water, to hazardous waste incineration/CH U	43.34	27.09
Electricity, high voltage, at grid/DE U	44.02	27.51
Lorry 28t/RER/I U	44.21	27.63
Lorry 40t/RER/I U	46.05	28.78
Uranium, enriched 3.8%, at USEC enrichment plant/US U	46.46	29.04
Disposal, refinery sludge, 89.5% water, to sanitary landfill/CH U	47.01	29.38
Gold, at refinery/TZ U	47.03	29.39
Butene, mixed, at plant/RER U	47.91	29.94
Phosphoric acid, fertiliser grade, 70% in H2O, at plant/MA U	47.94	29.96
Electricity, hydropower, at pumped storage power plant/ES U	48.91	30.57
Copper concentrate, at beneficiation/GLO U	50.13	31.33
Methyl-3-methoxypropionate, at plant/GLO U	51.85	32.40
Final repository for nuclear waste LLW/CH/I U	55.75	34.85
Natural gas, high pressure, at consumer/CZ U	57.13	35.71
Operation, freight train/CH U	58.09	36.31
Electricity, high voltage, at grid/GB U	58.65	36.66
Disposal, bitumen sheet, 1.5% water, to municipal incineration/CH U	60.19	37.62
Treatment, sewage, to wastewater treatment, class 1/CH U	61.03	38.14
Phenol, at plant/RER U	63.41	39.63
Electricity, high voltage, at grid/IT U	63.48	39.68
Natural gas, production DE, at long-distance pipeline/RER U	65.33	40.83
Hard coal coke, burned in stove 5-15kW/RER U	65.80	41.13
Lead, primary, at plant/GLO U	68.25	42.66
Electricity, hydropower, at reservoir power plant, alpine region/RER U	70.94	44.34
Natural gas, high pressure, at consumer/SK U	71.37	44.60
Cumene, at plant/RER U	72.61	45.38
Heavy fuel oil, burned in power plant/SI U	73.37	45.86
Crude oil, at production onshore/RU U	75.33	47.08
Acetic acid, 98% in H2O, at plant/RER U	76.47	47.79
Palladium, primary, at refinery/ZA U	77.11	48.19
Electricity, high voltage, at grid/US U	82.44	51.53
Natural gas, low pressure, at consumer/CH U	83.19	52.00
Nuclear spent fuel, in reprocessing, at plant/RER U	83.90	52.44
Crude oil, at production onshore/RAF U	86.20	53.88
Treatment, sewage, to wastewater treatment, class 2/CH U	87.25	54.53
Isopropanol, at plant/RER U	88.04	55.03
Natural gas, at production/RNA U	96.82	60.51
Kraft paper, unbleached, at plant/RER U	99.24	62.03
Gold, at refinery/ZA U	102.50	64.06
Crude oil, at production offshore/GB U	109.15	68.22

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	**500m Gantry Spacing**	**800m Gantry Spacing**
Copper concentrate, at beneficiation/RLA U	109.48	68.43
Crude oil, at production onshore/RME U	114.61	71.63
Electricity, hydropower, at pumped storage power plant/DE U	115.13	71.96
Natural gas, burned in gas motor, for storage/DE U	120.33	75.21
Copper, primary, at refinery/GLO U	120.36	75.22
Wood preservative, inorganic salt, containing Cr, at plant/RER S	122.06	76.29
Operation, passenger car/RER U	122.72	76.70
Natural gas, high pressure, at consumer/BE U	127.43	79.64
Natural gas, production NO, at long-distance pipeline/RER U	127.79	79.87
Electricity, high voltage, production BA, at grid/BA U	128.31	80.19
Operation, van < 3,5t/CH U	128.35	80.22
Copper, from imported concentrates, at refinery/DE U	129.10	80.69
Carbon dioxide liquid, at plant/RER U	129.37	80.85
Dichloromethane, at plant/RER U	130.47	81.54
Electricity, medium voltage, at grid/CH U	133.65	83.53
Methanol, at plant/GLO U	134.72	84.20
Gold, from combined gold-silver production, at refinery/CL U	137.13	85.71
Copper, primary, at refinery/RLA U	137.97	86.23
Disposal, residues, mechanical treatment, industrial device, in MSWI/CH U	143.16	89.47
Heavy fuel oil, burned in power plant/FI U	143.87	89.92
Power sawing, without catalytic converter/RER U	145.70	91.06
Electricity, medium voltage, production BA, at grid/BA U	145.82	91.14
Natural gas, production DZ, at long-distance pipeline/RER U	146.14	91.34
Tetrachloroethylene, at plant/WEU U	147.38	92.11
Ferromanganese, high-coal, 74.5% Mn, at regional storage/RER U	149.16	93.22
Natural gas, high pressure, at consumer/HU U	151.98	94.98
Diesel, at refinery/RER U	152.90	95.56
Electricity, medium voltage, at grid/US U	155.95	97.47
Electricity, medium voltage, production NORDEL, at grid/NORDEL U	161.31	100.82
Electricity, hydropower, at pumped storage power plant/GB U	162.46	101.54
Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	162.91	101.82
Copper, primary, at refinery/RNA U	163.33	102.08
Copper concentrate, at beneficiation/RNA U	163.83	102.40
Electricity, hydropower, at reservoir power plant/FI U	165.80	103.62
Trichloromethane, at plant/RER U	167.00	104.37
Natural gas, production NL, at long-distance pipeline/RER U	177.53	110.96
Production efforts, diodes/GLO U	179.12	111.95
Trimethylamine, at plant/RER U	181.70	113.56
Disposal, polyurethane, 0.2% water, to municipal incineration/CH U	195.75	122.35
Natural gas, at production offshore/NO U	196.17	122.61
Electricity, high voltage, production CENTREL, at grid/CENTREL U	199.12	124.45
Natural gas, high pressure, at consumer/FR U	201.64	126.02
Polypropylene, granulate, at plant/RER U	215.03	134.39
Natural gas, at production offshore/NL U	217.97	136.23
Transport, natural gas, pipeline, long distance/DE U	218.24	136.40
Zeolite, slurry, 50% in H2O, at plant/RER S	223.97	139.98
Steel, electric, un- and low-alloyed, at plant/RER U	228.37	142.73
Electricity, at cogen with biogas engine, allocation exergy/CH U	230.20	143.88
Electricity, medium voltage, production CENTREL, at grid/CENTREL U	230.44	144.03
Heavy fuel oil, at refinery/RER U	236.68	147.92
Uranium, enriched 3.9%, at USEC enrichment plant/US U	244.97	153.10
Sodium cyanide, at plant/RER U	245.45	153.40

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Water, ultrapure, at plant/GLO U	248.64	155.40
Electricity, high voltage, at grid/CH U	253.73	158.58
Natural gas, production RU, at long-distance pipeline/RER U	256.11	160.07
Nickel, 99.5%, at plant/GLO U	259.05	161.91
Natural gas, high pressure, at consumer/ES U	260.03	162.52
Uranium, enriched 4.0%, at USEC enrichment plant/US U	269.90	168.68
Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U	285.75	178.59
Gold, from combined gold-silver production, at refinery/PG U	287.07	179.42
Electricity, high voltage, production NORDEL, at grid/NORDEL U	291.29	182.06
Palladium, primary, at refinery/RU U	294.14	183.84
Biogas, from sewage sludge, at storage/CH U	300.17	187.61
Gold, from combined gold-silver production, at refinery/PE U	303.65	189.78
Acrylic acid, at plant/RER U	305.03	190.65
Natural gas, liquefied, at liquefaction plant/DZ U	306.90	191.81
Treatment, wafer fabrication effluent, to wastewater treatment, class 2/CH U	312.03	195.02
Gold, at refinery/AU U	323.17	201.98
Operation, lorry 3.5-16t, fleet average/RER U	324.76	202.98
Natural gas, burned in gas motor, for storage/NL U	340.30	212.69
Hard coal, at mine/RLA U	346.85	216.78
Operation, lorry >28t, fleet average/CH U	357.04	223.15
Ethylene oxide, at plant/RER U	358.17	223.86
Natural gas, high pressure, at consumer/NL U	363.89	227.43
Transport, natural gas, pipeline, long distance/NL U	365.23	228.27
Parkes process crust, from desilverising of lead/GLO U	367.11	229.44
Heat, at cogen 1MWe lean burn, allocation exergy/RER U	371.63	232.27
Vinyl chloride, at plant/RER U	403.92	252.45
Natural gas, at production offshore/GB U	414.27	258.92
Gold, at refinery/US U	423.90	264.94
Steel, converter, chromium steel 18/8, at plant/RER U	433.11	270.69
Toluene, liquid, at plant/RER U	433.14	270.71
Electricity, high voltage, aluminium industry, at grid/GLO U	446.44	279.03
Natural gas, burned in gas motor, for storage/RU U	472.82	295.51
Operation, freight train, diesel/RER U	489.38	305.86
Disposal, wire plastic, 3.55% water, to municipal incineration/CH U	490.86	306.79
Butadiene, at plant/RER U	492.12	307.57
Natural gas, high pressure, at consumer/DE U	494.79	309.25
Crude oil, at production offshore/NO U	515.49	322.18
Natural gas, production GB, at long-distance pipeline/RER U	521.44	325.90
Natural gas, at production onshore/NL U	522.19	326.37
Disposal, PE sealing sheet, 4% water, to municipal incineration/CH U	536.05	335.03
Nylon 6, at plant/RER U	550.83	344.27
Electricity, low voltage, production GB, at grid/GB U	557.81	348.63
Transport, natural gas, offshore pipeline, long distance/NO U	573.83	358.64
Transport, natural gas, onshore pipeline, long distance/DZ U	580.25	362.66
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	582.61	364.13
Copper concentrate, at beneficiation/RER U	582.78	364.24
Heavy fuel oil, burned in power plant/SE U	585.01	365.63
Carbon black, at plant/GLO U	589.55	368.47
Natural gas, at consumer/RNA U	594.78	371.74
Heavy fuel oil, burned in power plant/DK U	600.49	375.30
Heavy fuel oil, burned in power plant/CS U	607.36	379.60
Hard coal, burned in power plant/NPCC U	623.35	389.59

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Natural gas, unprocessed, at extraction/RNA U	631.44	394.65
Sulphur hexafluoride, liquid, at plant/RER U	633.19	395.74
Transport, natural gas, onshore pipeline, long distance/NO U	641.33	400.83
Transmission network, electricity, medium voltage/CH/I U	650.41	406.50
Rock wool, at plant/CH U	672.10	420.06
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/CH U	702.48	439.05
Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U	731.69	457.30
Electricity, hydropower, at reservoir power plant, non alpine regions/RER U	766.27	478.92
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	767.81	479.88
Natural gas, at production onshore/DE U	774.95	484.34
Charcoal, at plant/GLO U	783.29	489.56
Operation, barge tanker/RER U	809.21	505.75
Hard coal, burned in power plant/FRCC U	817.10	510.69
Hydrogen, cracking, APME, at plant/RER U	845.50	528.44
Hard coal, burned in power plant/ERCOT U	876.94	548.09
Styrene, at plant/RER U	896.81	560.51
Transport, liquefied natural gas, freight ship/OCE U	907.43	567.14
Polyethylene, LDPE, granulate, at plant/RER U	916.10	572.56
Tin, at regional storage/RER U	916.33	572.70
Natural gas, high pressure, at consumer/IT U	955.67	597.30
Magnesium oxide, at plant/RER U	966.54	604.09
Natural gas, burned in boiler condensing modulating >100kW/RER U	988.32	617.70
Crude oil, used in drilling tests/GLO U	1,028.40	642.75
Excavation, hydraulic digger/RER U	1,048.60	655.37
Pellets, iron, at plant/GLO U	1,091.39	682.12
Disposal, expanded polystyrene, 5% water, to municipal incineration/CH U	1,115.73	697.33
Transport, municipal waste collection, lorry 21t/CH U	1,167.26	729.54
Polyvinylchloride, emulsion polymerised, at plant/RER U	1,203.61	752.25
Transport, natural gas, pipeline, long distance/RER U	1,206.30	753.94
Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH U	1,217.64	761.03
Polystyrene, expandable, at plant/RER U	1,263.51	789.69
Ferronickel, 25% Ni, at plant/GLO U	1,285.00	803.12
Excavation, skid-steer loader/RER U	1,339.88	837.43
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U	1,350.72	844.20
Natural gas, production DZ, at evaporation plant/RER U	1,362.43	851.52
Titanium dioxide, chloride process, at plant/RER S	1,419.19	886.99
MG-silicon, at plant/NO U	1,437.70	898.56
Operation, aircraft, freight/RER U	1,474.14	921.34
Natural gas, burned in gas motor, for storage/NO U	1,477.20	923.25
Heavy fuel oil, burned in refinery furnace/MJ/CH U	1,480.38	925.24
Blasting/RER U	1,542.03	963.77
Electricity, at cogen 500kWe lean burn, allocation exergy/CH U	1,606.61	1,004.13
Operation, van < 3,5t/RER U	1,673.88	1,046.17
Titanium dioxide at plant, sulphate process, at plant/RER S	1,693.01	1,058.13
Benzene, at plant/RER U	1,731.52	1,082.20
Heavy fuel oil, burned in power plant/HU U	1,777.05	1,110.66
Natural gas, burned in gas turbine, for compressor station/DE U	1,822.08	1,138.80
Chlorodifluoromethane, at plant/NL U	1,871.52	1,169.70
Electricity, hydropower, at reservoir power plant/BR U	1,876.38	1,172.74
Xylene, at plant/RER U	1,920.42	1,200.26
Refinery gas, burned in flare/GLO U	1,927.72	1,204.82

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Natural gas, high pressure, at consumer/RER U	1,972.56	1,232.85
Propylene, at plant/RER U	2,079.84	1,299.90
Hard coal, burned in power plant/SPP U	2,130.57	1,331.61
Copper, primary, at refinery/RER U	2,139.05	1,336.90
Anode, aluminium electrolysis/RER U	2,247.42	1,404.64
Hard coal, burned in power plant/MRO U	2,330.28	1,456.43
Ammonia, partial oxidation, liquid, at plant/RER U	2,427.84	1,517.40
Operation, lorry 3.5-20t, fleet average/CH U	2,442.15	1,526.35
Biogas, from biowaste, at storage/CH U	2,541.03	1,588.14
Ethylene, average, at plant/RER U	2,659.07	1,661.92
Steel, converter, unalloyed, at plant/RER U	2,892.56	1,807.85
Lignite, burned in power plant/AT U	2,918.10	1,823.81
Coke oven gas, at plant/GLO U	2,943.72	1,839.82
Acetone, liquid, at plant/RER U	3,082.91	1,926.82
Natural gas, at production onshore/DZ U	3,089.60	1,931.00
Tetrafluoroethylene, at plant/RER U	3,161.19	1,975.74
Natural gas, burned in gas turbine, for compressor station/NL U	3,175.33	1,984.58
Heavy fuel oil, burned in power plant/HR U	3,292.02	2,057.52
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	3,315.66	2,072.29
Hard coal, burned in power plant/WECC U	3,408.77	2,130.48
Hard coal, at mine/CPA U	3,435.58	2,147.24
Operation, barge/RER U	3,484.75	2,177.97
Light fuel oil, burned in boiler 10kW, non-modulating/CH U	3,505.97	2,191.23
Heavy fuel oil, burned in power plant/AT U	3,560.30	2,225.19
Heavy fuel oil, burned in power plant/BE U	3,707.40	2,317.12
Peat, burned in power plant/NORDEL U	3,991.38	2,494.61
Hard coal coke, at plant/RER U	4,015.13	2,509.46
Refinery gas, burned in furnace/MJ/CH U	4,591.99	2,870.00
Hard coal, at mine/RU U	4,727.60	2,954.75
Heavy fuel oil, burned in power plant/NL U	4,728.97	2,955.61
Sour gas, burned in gas turbine, production/MJ/NO U	5,123.47	3,202.17
Natural gas, high pressure, at consumer/GB U	5,503.59	3,439.74
Natural gas, burned in power plant/US U	5,517.21	3,448.26
Polyethylene, HDPE, granulate, at plant/RER U	5,524.66	3,452.91
Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U	5,603.15	3,501.97
Electricity, at cogen 1MWe lean burn, allocation exergy/RER U	5,743.33	3,589.58
Electricity, high voltage, production GB, at grid/GB U	5,770.06	3,606.29
SOx retained, in hard coal flue gas desulphurisation/RER U	5,803.02	3,626.89
Drying, natural gas/NO U	5,858.67	3,661.67
Natural gas, burned in power plant/NORDEL U	5,972.73	3,732.95
Polyvinylchloride, suspension polymerised, at plant/RER U	6,268.41	3,917.75
Hard coal, at mine/AU U	6,452.75	4,032.97
Natural gas, burned in gas turbine, for compressor station/DZ U	6,673.51	4,170.94
Steel, converter, low-alloyed, at plant/RER U	7,062.84	4,414.27
Heavy fuel oil, burned in power plant/SK U	7,274.16	4,546.35
Lignite, at mine/RER U	7,624.09	4,765.06
SOx retained, in lignite flue gas desulphurisation/GLO U	7,794.33	4,871.46
Brick, at plant/RER U	8,337.02	5,210.64
Hard coal, at mine/RNA U	8,383.17	5,239.48
Sweetening, natural gas/DE U	8,760.48	5,475.30
Operation, freight train/RER U	8,912.74	5,570.46
Nylon 66, glass-filled, at plant/RER U	8,914.41	5,571.51
Heavy fuel oil, burned in power plant/CZ U	9,190.81	5,744.26

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Hard coal, burned in power plant/SK U	9,250.19	5,781.37
Natural gas, burned in industrial furnace low-NOx >100kW/RER U	9,728.86	6,080.54
Magnesium, at plant/RER U	9,793.27	6,120.79
Hard coal, burned in power plant/RFC U	9,893.95	6,183.72
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	9,934.38	6,208.99
Electricity, medium voltage, production UCTE, at grid/UCTE U	10,103.44	6,314.65
Natural gas, burned in gas turbine, for compressor station/NO U	10,139.97	6,337.48
Electricity, high voltage, production UCTE, at grid/UCTE U	10,321.14	6,450.71
Heavy fuel oil, burned in power plant/FR U	10,481.59	6,550.99
Natural gas, burned in gas turbine, for compressor station/UCTE U	10,585.80	6,616.12
Electricity, medium voltage, production GB, at grid/GB U	10,707.71	6,692.32
Ammonia, steam reforming, liquid, at plant/RER U	11,110.72	6,944.20
Operation, transoceanic tanker/OCE U	11,722.26	7,326.42
Disposal, solvents mixture, 16.5% water, to hazardous waste incineration/CH U	11,725.99	7,328.75
Hard coal, burned in power plant/SERC U	12,295.13	7,684.46
Heavy fuel oil, burned in power plant/PT U	12,369.72	7,731.07
Natural gas, sour, burned in production flare/MJ/GLO U	12,393.82	7,746.14
Natural gas, at production onshore/RU U	12,972.09	8,107.56
Hard coal, burned in power plant/HR U	13,056.43	8,160.27
Flat glass, uncoated, at plant/RER U	13,561.79	8,476.12
Natural gas, burned in gas motor, for storage/DZ U	13,626.57	8,516.60
Lignite, burned in power plant/SI U	14,238.22	8,898.89
Lignite, burned in power plant/SK U	14,351.14	8,969.46
Hard coal, at mine/ZA U	15,145.68	9,466.05
Hard coal, burned in power plant/NORDEL U	15,187.39	9,492.12
Nylon 66, at plant/RER U	15,494.67	9,684.17
Nitric acid, 50% in H2O, at plant/RER U	15,952.54	9,970.34
Lignite, burned in power plant/MK U	16,616.53	10,385.33
Heavy fuel oil, burned in power plant/GR U	17,006.95	10,629.34
Coke oven gas, burned in power plant/RER U	17,219.43	10,762.14
Natural gas, burned in power plant/AT U	17,302.35	10,813.97
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH U	17,637.23	11,023.27
Sweet gas, burned in gas turbine, production/MJ/NO U	18,873.58	11,795.99
Epoxy resin, liquid, at plant/RER U	19,135.27	11,959.54
Heavy fuel oil, burned in refinery furnace/MJ/RER U	19,373.55	12,108.47
Hard coal, burned in power plant/CZ U	21,060.26	13,162.66
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	22,907.96	14,317.47
Natural gas, burned in power plant/FR U	23,070.91	14,419.32
Quicklime, in pieces, loose, at plant/CH U	23,099.59	14,437.24
Natural gas, burned in boiler modulating >100kW/RER U	23,709.20	14,818.25
Natural gas, vented/GLO U	24,490.10	15,306.31
Hydrogen cyanide, at plant/RER U	24,980.25	15,612.65
Heavy fuel oil, burned in power plant/DE U	26,277.57	16,423.48
Sinter, iron, at plant/GLO U	29,134.07	18,208.79
Natural gas, burned in power plant/BE U	29,150.82	18,219.26
Operation, lorry 20-28t, fleet average/CH U	29,220.84	18,263.03
Lignite, burned in power plant/ES U	31,334.46	19,584.04
Light fuel oil, burned in industrial furnace 1MW, non-modulating/CH U	31,605.18	19,753.24
Wafer, fabricated, for integrated circuit, at plant/GLO U	32,423.81	20,264.88
Hard coal, burned in power plant/AT U	32,573.85	20,358.66
Natural gas, sweet, burned in production flare/MJ/GLO U	32,744.64	20,465.40

Ecoinvent Unit Process per km up to 2020 (Cut-off at < 0.1 kg CO_2 eqv.)	500m Gantry Spacing	800m Gantry Spacing
Operation, lorry >16t, fleet average/RER U	33,169.08	20,730.68
Transport, natural gas, pipeline, long distance/RU U	35,993.71	22,496.07
Refinery gas, burned in furnace/MJ/RER U	41,917.06	26,198.16
Lignite, burned in power plant/HU U	42,121.72	26,326.08
Natural gas, burned in power plant/UCTE U	44,632.54	27,895.34
Heavy fuel oil, burned in power plant/GB U	45,865.50	28,665.94
Hard coal, burned in industrial furnace 1-10MW/RER U	48,818.68	30,511.68
Natural gas, burned in gas turbine, for compressor station/RU U	49,027.97	30,642.48
Hard coal, at mine/EEU U	53,321.77	33,326.11
Heavy fuel oil, burned in power plant/ES U	54,557.04	34,098.15
Natural gas, burned in power plant/CENTREL U	60,024.16	37,515.10
Operation, transoceanic freight ship/OCE U	62,369.53	38,980.96
Diesel, burned in diesel-electric generating set/GLO U	62,784.39	39,240.24
Aluminium, primary, liquid, at plant/RER U	64,664.58	40,415.36
Natural gas, burned in power plant/ES U	64,975.13	40,609.46
Natural gas, burned in power plant/DE U	78,443.18	49,026.99
Hard coal, burned in power plant/BE U	79,450.11	49,656.32
Lignite, burned in power plant/BA U	79,809.73	49,881.08
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	85,661.51	53,538.45
Lignite, burned in power plant/CS U	90,402.47	56,501.55
Natural gas, burned in power plant/NL U	91,269.16	57,043.23
Hard coal, burned in power plant/PT U	96,593.04	60,370.65
Pig iron, at plant/GLO U	96,648.39	60,405.24
Polycarbonate, at plant/RER U	99,250.25	62,031.40
Heavy fuel oil, burned in power plant/IT U	108,947.26	68,092.04
Lignite, burned in power plant/GR U	118,149.39	73,843.37
Hard coal, at mine/WEU U	133,491.19	83,431.99
Hard coal, burned in power plant/NL U	159,172.77	99,482.98
Blast furnace gas, burned in power plant/RER U	175,542.95	109,714.34
Hard coal, burned in power plant/FR U	183,422.60	114,639.13
Lignite, burned in power plant/CZ U	189,248.45	118,280.28
Natural gas, burned in power plant/IT U	198,667.65	124,167.28
Hard coal, burned in power plant/IT U	217,475.52	135,922.20
Lignite, burned in power plant/PL U	228,525.72	142,828.57
Hard coal, burned in power plant/PL U	274,954.49	171,846.56
Diesel, burned in building machine/GLO U	276,714.57	172,946.61
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	285,939.41	178,712.13
Natural gas, burned in industrial furnace >100kW/RER U	330,537.54	206,585.96
Hard coal, burned in power plant/ES U	416,629.38	260,393.36
Lignite, burned in power plant/DE U	501,140.60	313,212.87
Natural gas, burned in power plant/GB U	760,993.08	475,620.67
Hard coal, burned in power plant/DE U	949,799.90	593,624.94
Clinker, at plant/CH U	977,944.50	611,215.31