Development of an Optimisation Model for Scheduling of Street Works Schemes

Rahman Pilvar

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy (PhD)

The University of Leeds
Institute for Transport Studies (ITS)

March 2015

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Acknowledgements

I thank the Almighty God for all his favours to me, especially giving me the physical and mental health and ability to study, work and live under his guidance.

The current research study was undertaken by the generous sponsorship from the Engineering and Physical Sciences Research Council (EPSRC), and was facilitated by the Institute for Transport Studies (ITS) at Leeds University. I wish to sincerely thank those at these organisations who helped me with obtaining this opportunity, particularly Prof Watling and Prof Shepherd. I would also like to thank all of the ITS and University of Leeds staff who supported my study in various direct or indirect ways during my study period.

I am extremely indebted to my supervisors Mr Frank Montgomery and Prof Nigel Smith, and wish to thank them beyond words for their invaluable support, advice and patience throughout my study period which helped me complete this PhD degree.

I am so grateful to my parents for everything I have in my life, including giving me the supports which I needed to undertake my higher education degrees.

Studying for this degree while being in full time employment involved devoting a lot of my time and energy that should have been otherwise spent for my family. My wife Sara and my parents in law, towards whom I extend my deepest gratitude, provided great assistance by bearing some of my parental responsibilities on many occasions.

Last but not least I would like to express my sincere thanks to my present employer RSSB who showed a great deal of understanding and cooperation, mainly by allowing me to have the level of flexibility in work which I needed for private study.

Rahman Pilvar
March 2015

Abstract

The coordination of street works activities in urban networks has been highlighted by the Government as one of the most important aspects of street works practice, benefiting street authorities, undertakers and road users alike (Department for Transport, 2012c). The present research aims to develop an optimisation model for minimising the overall costs and disruptions incurred by all stakeholders as a result of implementing a number of street works schemes in an urban traffic network. The output of the optimisation model consists of optimum values for the underlying decision variables of the model such as start time of each street works scheme, type of traffic management strategy for each link, sequence of link closures and the level of resources allocated to undertake each scheme.

The following two distinct objective functions, which are subject to minimisation by the optimisation model, have been developed:

- A primary objective function which captures the *monetised* effects of street works schemes such as cost of delays to road users, and cost of undertaking street works schemes.
- A secondary objective function (developed as a fuzzy inference system) to capture the non-monetised disruptive effects of street works schemes. The fuzzy variables of this inference system correspond to the level of 'accessibility degradation' of the network links, 'connectivity degradation' of the origin-destinations of the network, and 'time sensitivity' of the disruptive events (i.e. street works schemes).

Next the street works optimisation problem was mathematically formulated as a bi-level optimisation programming problem, where the higher level problem is associated with minimising the aforementioned objective functions, and the lower level problem deals with predicting traffic flows, and thus the amount of delays incurred by the road users.

Subsequently this study developed a genetic algorithm solution method to solve the resulting non-convex and NP-hard optimisation problem with integer or mixed type variables. Finally the performance of the optimisation algorithm was verified by a number of experimental tests on a small hypothetical network for three street works schemes.

Table of Contents

List of Tables

List of Figures

Chapter 1
Thesis Introduction

This chapter sets out the motivations and the objectives of the present research, and describes the underlying problem which is addressed by this study (sections 1.1 to 1.4). Next, the scope of this study is clarified (section 1.5), and finally a brief description of each chapter of the thesis is provided (section 1.6).

1.1. Research motivation

The number of work zones relating to street works on highways and urban roads is growing significantly in many countries. In the context of rural highways, such works mainly stem from the need for restoring and improving the ageing road infrastructure which has been identified as one of the grand challenges of engineering in the 21st century, so that in 2011 24% of all nonrecurring congestion on freeways (in the US) was due to work zone activities (Kim et al., 2011). In urban areas, this problem is exacerbated by the need to maintain, improve or commission new utilities buried underneath the roads.

In the United Kingdom Goodwin (2005) reported that, based on two independent research studies, the cost of congestion by utility works could range between £1 billion to £4.3 billion a year in 2002 prices. The cost of congestion due to road works on UK trunk roads and motorways which are administrated by the Highways Agency is estimated to be £200 million per year in 2002 prices (Bourne et al., 2008). These figures are likely to be higher in future years due to the growth of traffic and the aging of the existing infrastructure which will entail further construction and maintenance works on transportation networks.

The Government acknowledges that works by utilities and others with apparatus in the street and works carried out by or on behalf of highway authorities for road improvement purposes are necessary in order to provide and maintain essential services and transport networks on which the society depends. However these works can also cause significant disruption, imposing substantial costs on individuals and on the economy. The Government therefore considers that there is significant scope to reduce this disruption. The Government's strategy is based around providing the right powers, incentives and tools for all involved to identify and adopt best practice in the management and coordination of works (Department for Transport, 2012c).

The coordination of street works schemes has been set as a statutory duty for traffic network authorities in the United Kingdom, as it is a key means of minimising the inconvenience and costs caused by street works activities. For instance a best practice guidance on street works which has been published by UK Department for Transport (2012c) advocates **optimising** the timing of street works schemes, and provides some guidance on the evaluation of the impacts of traffic management schemes on local traffic. However the scope for optimisation in the context of planning street works is much wider:

An urban transportation network normally experiences time-varying traffic volumes and is subject to various restrictions and requirements for activities which entail road occupancy during the year. Therefore the delays and other costs and disruptions which are incurred by those affected by the schemes (road users, street works undertakers and their customers, local residents and public services, etc.) are dependent on a range of decision variables such as the timing of the works, level of working resources, amount of road space allocated for conducting the works, and sequence of the links subject to street works activities.

This gives rise to an opportunity for formulating an optimisation problem in order to find the most suitable values for these decision parameters which would result in minimising the overall costs and disruption to all of the stakeholders affected by the street works schemes. Subsequently an appropriate solution algorithm can be developed in order to solve the resulting optimisation problem.

Once available, such an optimisation model which can produce optimum schedules for the planned street works schemes in a network will be considered as a key coordination tool by traffic network authorities. However in order to develop an optimisation model in this context, a number of key issues need to be addressed first:

Importantly, the evaluation methodologies embedded in the optimisation model should be able to measure the trade-offs between the conflicting objectives of the stakeholders. For instance street works contractors may wish to have maximum road space available to them, and choose peak traffic hours for their activities. On the other hand residents and public services who are concerned by the resulting disruptions usually press for minimal closures and off-peak working hours. As such the objective function(s) of the model should be able to capture both the monetised costs and non-monetised disruptive effects which are incurred by the stakeholders.

The optimisation model should also allow for defining the constraints and conditions which are set for street works schemes in relation to the stakeholders. For instance this can include the latest acceptable completion times for the schemes, and avoiding conflict between two incompatible schemes being implemented on a link at the same time.

1.2. Objectives of the research

The overarching goal of this study is to develop a sound theoretical methodology, in the form of a mathematical optimisation model, which enables planners to schedule several street works schemes in a traffic network in such a way that the resulting costs and disruptions incurred by all relevant stakeholders are minimised.

In order to develop such optimisation model, one should be aware of the underlying procedures and requirements of street works practice. It also entails borrowing suitable *themes* (e.g. concepts, structures and methodologies) from other appropriate transportation related subjects. Bearing these in mind, the following six objectives have been identified for this research study:

1. To review the current practice of street works schemes, particularly in the context of the United Kingdom; also to review the most significant types of transportation related studies which are concerned with analysing transport networks subject to capacity degrading events and change of configuration.

2. To develop a methodology for measuring the underlying effects of street works activities, including monetised costs and non-monetised disruptive impacts incurred by the stakeholders

3. To formulate the street works optimisation problem in mathematical terms: this entails identifying the decision variables subject to optimisation, and establishing different levels and elements of the optimisation model and the way they interact with each other. The street works optimisation problem studied in this thesis is described in section 1.3.

Objectives 2 and 3 above are associated with devising the mathematical structure of an optimisation problem which will be used for scheduling of street works schemes. Once this problem is sufficiently analysed, a suitable and efficient solution algorithm for the optimisation problem should be devised which can promise finding optimum or near optimum solutions. This is associated with objectives 4 and 5 of this study. The final objective (objective 6) is associated with verifying the outcomes of objectives 2 to 5.

4. Once the problem which was previously formulated is sufficiently analysed, to find a suitable optimisation methodology for the street works optimisation problem.

5. Using this methodology, to develop a bespoke optimisation algorithm for the optimisation problem.
6. To verify the robustness of the optimisation model and the performance of its solution algorithm through undertaking a number of experimental tests using a small hypothetical traffic network.

1.3. Optimum scheduling of street works schemes: problem statement

The optimisation problem which is to be formulated and subsequently solved in this study can be worded, in general terms, as follows:

Several street works schemes are due to be implemented in a transportation network. The properties of the network including link characteristics, origin-destination demands, etc. are available and are regarded as inputs of the problem. The links of the network can be subject to varying hourly and day-to-day traffic demand. The links of the network have varying *sensitivity*, in terms of the *disruption* perceived by network users, at different times and to different traffic management arrangements. Such sensitivity and the resulting disruption will be explained by a qualitative measure.

For each street works scheme, many implementation scenarios are possible based on the decision parameters such as the start time of each scheme, sequence of the links subject to a scheme, type of traffic management strategy for each link, amount of resources to complete a scheme, and so on. Additional decision parameters may be included depending on the nature of each case at the discretion of the network planners. For instance idling times (working shift gaps) between the stages of a scheme could be allowed at a cost relating to the idling labour and equipment.

The inputs to the problem also include the unit rates and the formulae which are needed to calculate the monetised costs incurred by road users and street works undertakers. These, for instance, include average cost per each hour of delay, cost of labour and equipment per each shift of work, and so on. A cost function is also attributed to the completion date of each street works scheme (e.g. later completion can mean higher cost to street works undertakers), and there is normally limitation on the latest completion date of each scheme. All street works schemes will need to be completed during a planning period which has been set in advance by the planners.

Given the above-stated assumptions and information, the decision makers seek to select the most suitable street works scenarios (plan) for each scheme, in terms of causing minimal costs (monetised effects) and disruption (non-monetised effects) to the stakeholders. The underlying information associated with the most suitable scenarios which will need to be produced by the optimisation model include (but may not be limited to) the following:

- The start time of each scheme
- The type of traffic management used for undertaking each scheme on a link
- The sequence of links which will be subject to a street works scheme

1.4. Expected research contribution

Every year traffic authorities are faced with the problem of planning a significant number of street works schemes for the year ahead; and in so doing they have to account for the conflicting objectives of different stakeholders which are affected by these disruptive activities on streets. The planning exercise entails finding the most suitable (optimum) values for a range of decision variables relating to undertaking street works schemes, which often includes (but may not be limited to): the start time of each scheme, the type of traffic management for undertaking a scheme, and the sequence of the network links which should be subject to a scheme. However a robust framework which can enable undertaking such a planning exercise at a network-wide level was not found in the existing literature.

The present study intends to address this issue by developing an appropriate optimisation model with the following key features:

- While the optimisation model evaluates the monetised costs of street works through a primary objective function, it will also comprise a separate qualitative objective function to account for the non-monetised effects of street works. This function will be developed by adopting the fuzzy logic theory which is best suitable (as to be argued later) for evaluating the disruptive effects of street works on the accessibility of network users. Devising a robust and flexible methodology to measure disruption to transport networks is a major contribution of the present thesis to transport network studies.
- Inside the street works optimisation model, street works schemes are formulated as a project scheduling model which is quite familiar to project planners. In addition to its familiarity to the planners and the fact that this framework has been sufficiently studied in academia and practice (e.g. in terms of the solution algorithms for a project scheduling problem), using this framework can assist with modelling many different types of street works schemes in a traffic network (rather than, for instance, solely highway maintenance projects), and to address common

circumstances where undertaking several schemes at the same time on a single network is likely to prove beneficial.

- An appropriate optimisation algorithm will be developed to solve the resulting non-convex optimisation problem (which is intrinsically quite hard to be solved). The solution algorithm will warrant finding optimum or near optimum values for the underlying decision variables of the optimisation problem.

Once the optimisation model is developed, this study will verify its performance by using it to plan several street works schemes on a hypothetical traffic network so that the total costs and disruptive effects due to undertaking the schemes are minimised.

1.5. Scoping statements

The optimisation model of this study will need to borrow a number of concepts and methodologies from other types of transportation related studies. In particular this includes *traffic assignment* studies and the *network equilibrium* concept. Other relevant concepts are *reliability*, *vulnerability* and *accessibility* assessment of transport networks, and project scheduling studies. These subjects have been themselves subject to many studies over the years, and branch to several different types of models based on the underlying theories and assumptions which have been embedded in the process of their developments.

The accuracy of the results of the optimisation model of this study, for implementation on a real-life problem, will largely depend on the accuracy and appropriateness of the models borrowed from the aforementioned studies, as they are regarded as *sub-models* of the street works optimisation model studied in this thesis. Nonetheless this study merely intends to show **how** those sub-models can work together to serve the purpose of the optimisation model. The scope of this study excludes the development of bespoke types of these sub-models which may promise higher level of accuracy for the results of the optimisation model. However when different types of such models are introduced and reviewed, general overviews are presented about the circumstances where one model can be more appropriate than another in the underlying circumstances of using the optimisation model of this study.

By observing various optimisation studies which have been mentioned in this thesis, it is evident that the performance of an optimisation model depends on at least three factors, the first two of them being:

- Selection of an appropriate type of optimisation methodology to suit the type of the problem under question (factor 1).

- Formulating the problem under question in a robust way in order to capture the full capabilities of the selected optimisation methodology (factor 2).

The above requirements have been met for developing the optimisation model of this study, and are described mainly in chapters six and seven.

Nonetheless further improvements to the performance of an optimisation algorithm can still be achieved through modifying some of the key parameters of the selected optimisation model (factor three), such as the crossover and mutation ‘types’ and ‘rates’ of a genetic algorithm model. This normally involves undertaking a large number of *trial and error type* experiments on a wide range of examples. The most suitable parameters may also be different from one case to the other.

Factor three type of improvements which is introduced above is **out** of the scope of the present study. Rather the experimental tests presented in this thesis mainly intend to assist with proving the robustness of the formulation of the optimisation problem of this study, as well as illustrating the feasibility of the optimisation algorithm which is described in a general way in chapter seven.

Further remarks about the scoping of this study are provided in the relevant chapters of the thesis.

1.6. Key definitions

A number of key terms relating to the work undertaken in this study are explained in this section. These terms are frequently used in the following chapters:

- **Street works (**also with possible subtle differences: ***street works activities, street works schemes/projects,*** and ***utility works/schemes/projects*****):** In this thesis, street works refers to any type of on-street activities (e.g. road maintenance activities, utility repair and renewals schemes, etc.) which are normally undertaken in a planned way and result in degrading the capacity of the street which is subject to such works. A range of options may exist for undertaking a street works scheme (see the following item). The optimisation model of this study is concerned with finding the most suitable options for all street works schemes which are planned within a traffic network.
- **Street works scenario/option:** This is associated with a single option for undertaking a street works scheme in terms of: start time of each scheme, type of the traffic management schemes used for undertaking works on each link, sequence of the links subject to street works schemes, and so on. The optimisation model of this study aims to find the optimum option for each scheme which would

result in minimising the objective functions which have been set by the planners for the optimisation model.

- **(Optimum) scheduling of street works schemes:** This refers to the selection of a suitable, or preferably the *optimum*, option (as defined above) for undertaking a street works scheme.
- **The optimisation model:** The optimisation model of this study mainly comprises the decision variables, other input and output variables, and objective functions and their relationships in order to assist with finding the optimum schedules of the street works schemes which are planned for implementation in a traffic network (i.e. solving the optimisation problem). It may encompass – depending on the context - the solution algorithm devised to solve the optimisation problem.
- **The optimisation algorithm:** This refers to the optimisation algorithm which is devised, using a generic optimisation methodology (i.e. genetic algorithms), to solve the optimisation problem of this study.
- **The optimisation function:** It refers to the genetic algorithm optimisation function which is available in an optimisation package such as that provided by MATLAB (MathWorks Inc., 2014d). Once the optimisation algorithm is coded in MATLAB language, this function is executed to produce the optimum scenarios for the street works scheme.
- **Special events**: The classic definition of special events is provided in chapter 5 as "an occurrence that abnormally increases traffic demand" (Transportation Research Board, 2003). Under this definition, special events may include sporting events, parades, fairs and other planned events. However for the purpose of this study, the term special events is used more broadly to cover any conditions - not necessarily involving an increase in travel demand - where the disruption due to a planned degradation of network capacity would be regarded as much more serious than if the disruption were to occur in normal circumstances.
- **Network planners (**also **the planners, *network/traffic/highways authorities*):** These terms refer to the authorities which are responsible for evaluating street works permit applications (for the traffic networks under their jurisdictions), with a view to minimise resulting delays and disruptions.
- **Street works undertakers:** This refers to organisations such as utility companies, and highway maintenance contractors and clients which undertake or sponsor various types of on-street activities in the interests of their customers.
- **Traffic management strategy (**also ***traffic management arrangement/scheme)*:** These are measures which are intended to facilitate safe road works by temporary traffic restrictions and/or closures whilst keeping the

traffic flowing as freely as possible, and providing alternative routes for the road users when necessary. Traffic management options are usually distinguished by the amount of road space allocated to a street works scheme (e.g. a full closure or a lane closure arrangement).

- **Road/highway users:** This term refers to everybody who uses the footway or the carriageway (i.e. road travellers), whether for transport or access, or for recreation or business. It includes users of motorised and non-motorised vehicles, pedestrians and horse riders. It also includes people with disabilities and others whose mobility is hindered, e.g. by heavy shopping or by accompanying children (Department for Transport, 2007)
- **Work zone:** A work zone is defined in the (American) Highway Capacity Manual (Transportation Research Board, 2000) as "an area of a highway in which maintenance and construction operations are taking place that impinges on the number of lanes available to traffic and affect the operational characteristics of traffic flowing through the area."

1.7. Structure of the thesis

Following the present introductory chapter, several underlying aspects of street works activities, mainly in the context of the United Kingdom, are reviewed in chapter two. This primarily includes identifying the main challenges associated with the implementation of street works, the objectives and aspirations which have been specified by relevant organisations in relation to minimising the adverse impacts of street works, and relevant UK Government legislation in relation to the practice of street works. A section of this chapter will also review the topic of '*coordination of street works activities*', as advocated by relevant legislation and guidelines since it is directly related to the objectives of the present study.

In chapter three, several types of transport network analysis studies which are deemed potentially relevant to the subject of this study are reviewed (the process for selecting these subjects has been described in chapter 4). Chapter three firstly reviews the fundamental subject of traffic assignment models. It then continues by reviewing three subjects associated with transport networks subject to degrading effects, including *reliability*, *vulnerability* and *accessibility* assessment of transport networks. Finally the network design type of studies which are concerned with optimising the configuration of a transport network are reviewed. The reviews in this chapter mainly aim at identifying different elements of each of these subjects which can be incorporated into the optimisation model of this study.

Chapter four, dedicated to devising a roadmap for completion of this research, describes the steps which have been followed to achieve the objectives of this research study (as set out in chapter one). This mainly includes measuring the effects of street works, developing the street works scheduling optimisation model, and finding a suitable methodology to solve the optimisation model.

Chapter five is dedicated to explaining the development of the objective functions of the optimisation problem. An optimisation algorithm will then be tasked to minimise these objective functions concurrently, resulting in finding the most desirable scenarios for undertaking a number of street works activities:

- Initially the primary objective function of this study is formulated to account for the monetised costs of street works such as delay and vehicle maintenance costs (incurred by road users) and cost of utility works (incurred by street works undertakers).
- A secondary objective function is argued to be necessary in order to capture those effects of street works which are not normally captured by conventional evaluation models which only measure the above monetised costs. These non-monetised costs, associated with the secondary objective function, are collectively referred to as ‘disruption’ to links and origin-destinations of a transport network. It will be justified that the fuzzy logic theory is very likely to be the most suitable theory which can be utilised for measuring the disruptive effects of street works schemes. Examples of appropriate fuzzy membership functions will be provided for the proposed fuzzy variables which will be used in order to deduce the overall disruptive effects of street works activities implemented in a traffic network.

Chapter six is devoted to the formulation of the optimisation problem of this study in order to match the format of an established type of mathematical optimisation problem. This will be subsequent to the sufficient analysis of the optimisation problem and its underlying properties such as: levels of the problem, decision variables, objective functions and the way they interact with each other. Consequently a suitable optimisation methodology is recommended for solving the optimisation problem of this study.

In accordance with the genetic algorithm methodology which was recommended in chapter six, chapter seven deals with the development of a suitable optimisation algorithm. This chapter describes how the required elements of the selected genetic algorithm method such as coding of the individuals, crossover and mutation functions, and the fitness function of the model are selected or developed in order to suit the specific characteristics of the optimisation problem.

In chapter eight, the results of three experimental tests (each test includes several runs) are presented for the optimisation algorithm which was described and developed in previous chapters. Initially the optimisation model is applied to a small hypothetical network for three street works schemes to minimise the primary objective function of the model. Subsequently the same network schemes are used for minimising **both** of the objective functions for several other street works activities. Finally an experimental test is conducted on a hypothetical small size network.

Chapter nine is dedicated to reviewing the results obtained in previous chapters. In particular, comments are made as to how each of the objectives of this research study has been achieved as a result of the work undertaken. Subsequently the validation of this study is justified , and a number of opportunities for further research which have been discovered in this study will be highlighted.

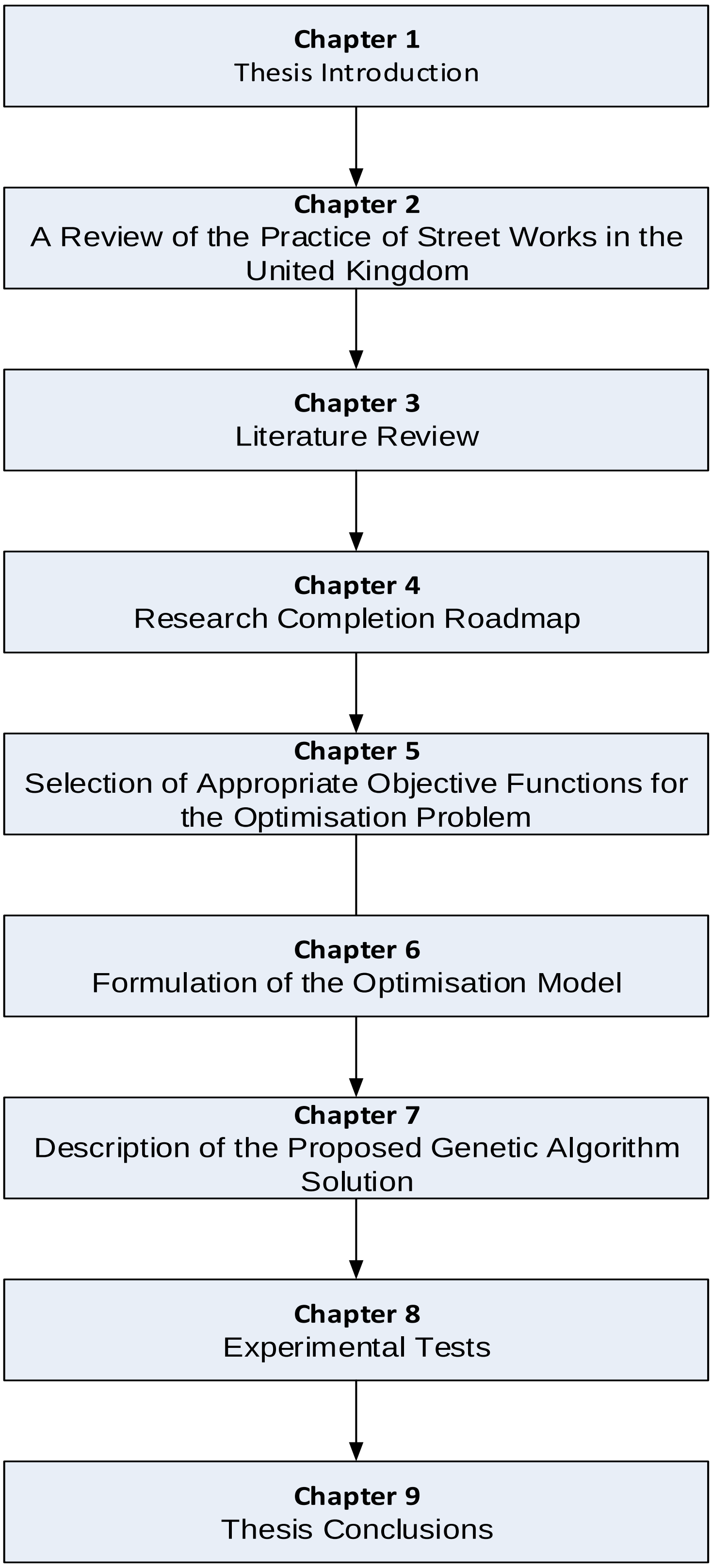


Figure 1-1 Structure of the thesis

Chapter 2
A Review of the Practice of Street Works in the United Kingdom

2.1. Introduction

Today roads and streets carry more than just traffic (Department for Transport, 2007): within them are the means to carry the energy, water and communications infrastructure to provide essential services to both homes and businesses. Streets also provide a key part of local public space where people can meet, talk and participate in their community. The asset management of these utilities and the highway networks containing them is of vital importance to the well-being of the members of the public and the overall economy of the country.

In the United Kingdom there is a vast network of utility and local authority infrastructure buried beneath highways and footways: Parker (2008) reports that the combined network of water, sewer, gas and electricity services extends to over 1.5 million km, which is almost five times longer than the country's road network. The data for telecommunications cables and local authority infrastructure (e.g. cabling for street lighting and traffic lights, highway drains and so on) are rather patchy but when estimates of these are taken into account, the total length of buried infrastructure could be well over 4 million kilometres.

Repair and maintenance of these utilities and the ageing road networks (e.g. see Figure 2-1) have posed significant cost and other issues for society; this includes delays incurred by road travellers, traffic management costs, difficulties in the reinstatement of pavements after utility works and damage to the existing utilities during street works.

Parker (2008) reports that to repair, maintain and upgrade this network of buried infrastructure the utility industry alone undertakes about 1.5 million street works annually: " …not surprisingly, this results in significant costs both to the utility industry and to society as a whole. The utility industry bears the direct construction costs of these works, such as the labour, material, planning, design and supervision costs. In addition, there are indirect costs to the utilities due, for example, to third-party damage to private property or other utility apparatus. The costs that are borne by society are the social costs incurred through, for example, delay to road users, disruption to businesses and the local community, increased levels of noise and air pollution, and damage to the environment."

Considering the issues described above, it is of paramount importance to find the right balance between the needs of the utility companies and asset owners seeking to maintain or improve essential services, and highway and traffic authorities striving to keep traffic moving for their road users.

The following sections mainly review the key areas of the management and coordination of street works schemes which can assist with striking this balance, and reducing various types of costs (as identified in the next section) which are posed to society by undertaking street works. The Department for Transport (2012c) believes that such better coordination and management of works will bring significant benefits to the public in terms of safety, congestion and disruption, environment and service.

2.2. The cost of street works borne by society

Works in the street will inevitably cause some disruption and costs through delays and congestion to all highway users; inconvenience to local residents, pedestrians and businesses; and intrusion into the local environment (Department for Transport, 2012c). Parker (2008) has identified the following costs resulting from street works:

(a) costs to highway users

(b) costs to business

(c) costs to the local community

(d) costs to the highway authority

(e) environmental costs

(f) safety (i.e. traffic accidents and injuries to site operatives).

Goodwin (2005) reports that utilities-related street works are responsible for about 5% of the total amount of congestion which is widely cited as about £20b per year, thus implying that the cost due to utilities' street works is about £1b per year (in 2005 prices), though other methods give a lower figure. Goodwin also reports a calculation by the Department for Transport which suggested that (in 2005 or shortly before) there were an estimated 7 million days of utilities' street works per year, the congestion they caused costing on average over £600 each, to produce an annual cost over four times larger, at £4.3 billion. Goodwin however suggests that these figures are likely to be exaggerated due to a number of problems embedded in the calculations such as the erroneous assumption that drivers never adapt their behaviour to avoid works (e.g. by travelling at different times of the day). However the real amount is still expected to be very significant.

2.3. Improving the practice of street works schemes

To improve the general practice of street works, a vision has been set for street works in the United Kingdom (NJUG, 2013) comprising the following six elements:

1. Safety is the number one priority

2. Damage to underground assets is avoided

3. Utilities work together and in partnership with local authorities to minimise disruption

4. Utilities deliver consistent high quality

5. Utilities maximise use of sustainable methods and materials

6. Street works in the UK are regarded as world class

In line with this vision and in order to tackle the challenges associated with buried utilities and street works schemes, a range of initiatives and measures has been observed at the European and national levels. Some of the most significant ones are reviewed below:

Geospatial mapping of the infrastructural assets, including underground utilities: Availability of sufficient information – in particular location and type data - about infrastructural assets such as highways and roads, bridges and underground utilities is vital for their timely and efficient maintenance, and helps with minimising disruption to the public. Furthermore as part of most infrastructure improvement projects, an important but very time-consuming stage of the feasibility and design studies is associated with the collection and then analysis of a range of information about the existing assets within the area of the scheme, for instance the location and depth of the utilities and the feasibility and cost of removing or relocating these facilities. However for a wide range of existing utilities, only old drawings are available which are not easy to be used in their current format (Cumberbatch, 2005). This issue has triggered several initiatives and research projects at the national and European levels. The most notable ones include:

- **The INSPIRE (Infrastructure for Spatial Information in the European Community) Directive:** This is a European directive which came into force in 2007 and will be fully implemented by 2019. It aims to create a European Union spatial data infrastructure. The spatial information considered under this directive is extensive and includes a great variety of topical and technical themes. The resulting European Spatial Data Infrastructure will enable the sharing of environmental spatial information – including that usable for street works undertakers - among public sector organisations, and will better facilitate public access to spatial information across Europe. It will also assist in policy-making across boundaries (European Commission, 2014). The importance of such data for infrastructural assets has increased significantly in recent years due to the increasing maturity of virtual and augmented reality technology tools such as Google Glass. Therefore new windows of opportunities have been opened for speedy identification of underground utilities within an area by the engineers, and subsequently take appropriate decisions in order to minimise the length and duration of disruptive works.

- **Digital National Framework (DNF):** DNF is introduced as a set of principles, concepts and methods evolved through best practice with the intention of establishing better integrity, promoting greater reuse and easier sharing of application information. It aims to enable and promote the integration and sharing of location-based information from multiple sources in the United Kingdom (DNF, 2011). Similar initiatives at national level such as the development of a location strategy for the United Kingdom has been undertaken to maximise the use of geographic information in various industries (Communities and Local Government, 2008).
- **VISTA (Visualising integrated information on buried assets to reduce street works):** This project aims to bring together existing paper and digital records with data from satellite and ground-based positioning systems. This coordinated data system will be used to create a three-dimensional map of pipes and cables buried underground. (Institution of Civil Engineers, 2014)
- **Mapping the Underworld (MTU):** This research project seeks to develop the means to locate, map in 3-D and record the position of all buried utility assets without excavation through using a single shared multi-sensor platform. The project also aims to create a prototype multi-sensor device and undertake fundamental enabling research for the location of underground utilities through combining novel ground penetrating radar and acoustics and low frequency active and passive electromagnetic field approaches (Hamilton, 2012)
- **Vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communication systems:** Recently a lot of research and development activities have been dedicated to the development of v2v, v2i and v2x communication systems (e.g. see D'Arcy, 2013; NewsRITA, 2014) which can provide a range of envisaged benefits to the users of traffic networks, including giving first-hand and real-time information to the drivers about the relevant road works on a traffic network, and providing necessary directions to mitigate their adverse effects (hazards, delays, and so on.)

Establishing advisory organisations: This is in order to raise awareness, and develop and promote good practice guidelines for those involved in street works**:** The most prominent ones include the National Joint Utility Group (NJUG), Highway Authorities & Utilities Committee HAUC (UK), and the National Underground Asset Group (NAUG). These organisations have published a range of guidelines on street works legislation and operation, and good practice advice and case studies about various aspects of undertaking street works (e.g. protection of assets, reinstatements, traffic management, cooperation between stakeholders, and coordination of works).

Lane Rental Schemes: Under the New Roads and Street Works Act 1991 (NRSWA) a daily charge to the undertakers is applicable or each working day that the works exceed the longer of the prescribed or reasonable periods. However under the recently introduced Lane Rental Schemes, street works undertakers can be required to pay a daily charge for occupation of the highway from the start of a scheme: "Section 74A of NRSWA enables highway authorities, with the approval of the Secretary of State, to charge street works undertakers a daily charge for each day during which their works occupy the highway – commonly referred to as *"lane rental"* schemes" (Department for Transport, 2012b).

The Government (Department for Transport, 2012b) requires lane rental schemes to be focused on the very busiest streets at the busiest times. The potential advantage of lane rental schemes is that they provide real financial incentives that encourage works promoters to:

- reduce the length of time that sites are unoccupied (associated with idling times), hence reducing total works durations;
- improve planning, coordination and working methods to maximise efficiency;
- carry out more works outside of peak periods, reopening the highway to traffic at the busiest times (e.g. by plating over their excavations) and/or making greater use of evening or weekend working where the local environmental impact is acceptable;
- **optimise** the number of operatives on site to enable works to be completed as quickly as possible;
- complete works to the required standard first time, and with permanent reinstatement, reducing the need to return to the site to carry out remedial works.

Application of Information Technology (IT) and Intelligent Transportation Systems (ITS): Some examples include: informing the travellers of road-works ahead through live traffic information , selection of the best timing and layout of the works to cause minimal disruption (e.g. see Figure 2-3), online portals to provide live or near-live information about street works schemes (e.g. see Figure 2-4), and future application of vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communication systems (RITA, 2014) in order to share live information about traffic conditions among vehicles and infrastructure.

More misery on London roads as potholes toll soars to 121,000

Pippa Crerar
City Hall Editor

A HUGE rise in the number of potholes in London's roads was revealed today as councils struggle to keep up with road maintenance.

The number soared from 79,299 cracks and craters last year to 121,299 in 2009-10 – a 57 per cent increase. The cost of repairs also soared with the capital's 33 boroughs spending £8.3 million – or £68 a hole – this year, up from £5.6 million.

It comes after the Standard exposed a record 370,000 sets of roadworks over the past 12 months. Londoners now face months more misery as coun-

Struggle: potholes cost £68 each

works that typically reduce the life of road surfaces by a third, while the utility firms insist they are under pressure to complete the work efficiently

Figure 2-1 The deteriorated condition of roads has been a matter of concern to the public in many major cities such as London (London Evening Standard, 2010)

June 12, 2013

Utility companies could face roadworks fines in Kent

Kent County Council has launched a scheme that aims to reduce congestion on the county's busiest roads.

Under the new Kent lane rental scheme, companies will now be charged up to £2,000 per day for the inconvenience caused by digging up the busiest roads on the network at peak times.

Kent is the first county council in the country to run the scheme, which aims to push utility contractors to work on the roads during the night and at off-peak times or to use techniques such as tunnelling more often to avoid closing the road altogether.

The scheme covers more than 465 roads in Kent in the areas most susceptible to major roadwork disruption. Revenue generated from the scheme will be invested in further work to cut congestion in Kent.

Figure 2-2 A highway authority in England has introduced a lane rental scheme for reducing delays on busy streets at peak times (Highways Magazine, 2013)

Figure 2-3 Application of the Dynamic Road-space Utilisation Manager (DRUM) to deduce the optimum time for lane closures during road maintenance works (TRL, 2007)

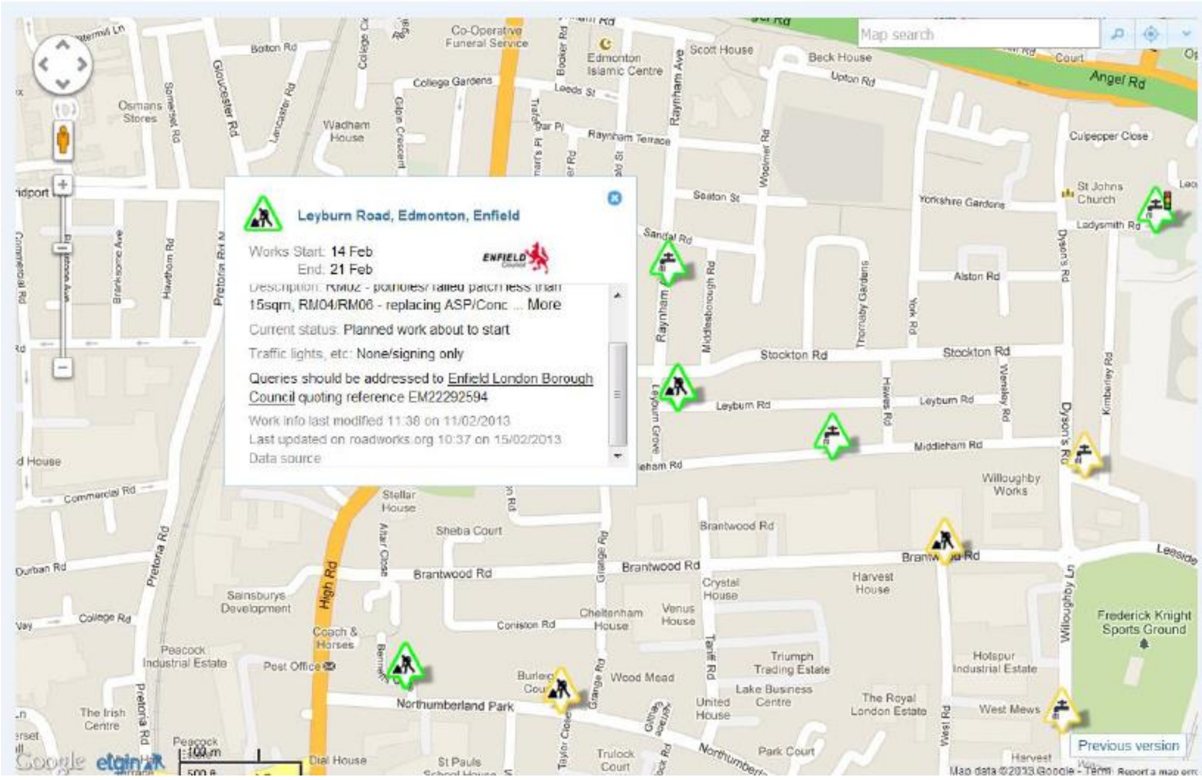


Figure 2-4 A snapshot of the map provided on the LondonWorks portal (Transport for London, 2014)

(Providing information about planned street works in a London area)

2.4. Statistatutory responsibilities of the various parties involved in working in the street

In the United Kingdom, street works are subject to some legislative rules and regulations which impose a range of duties on network authorities as well as street works undertakers. The most significant ones are introduced in this section:

A local authority in the United Kingdom has a statutory duty, in accordance with **New Roads and Street Works Act 1991** (Section 59), to manage its road network effectively with a view to keeping traffic moving (NJUG, 2013). Street authorities must:

“use their best endeavours to coordinate the execution of works of all kinds (including works for road purposes and the carrying out of relevant activities) in streets for which they are responsible:

a) *In the interest of safety*

b) *To minimise the inconvenience to persons using the street (having regard, in particular, to the needs of people with a disability)*

c) *To protect the structure of the street and the integrity of apparatus in it."*

Furthermore local authorities need to have regard for the **Network Management Duty Guidance** (Department for Transport, 2004b) which requires them to establish processes of identifying (potential) causes of road congestion or other disruption to the movement of traffic on their road network. In doing so they must consider any possible action that could be taken in response or in anticipation of such causes. It also requires every local authority to assess its performance in managing its road network and review the effectiveness of its arrangements.

Under the **New Roads and Street Works Act (1991)** and **The Street Works (Registers, Notices, Directions and Designations) (England) Regulations 2007**, local authorities have a duty to *coordinate* street works:

- *"Authorities are required to co-ordinate works on their streets, including both their own works and those carried out by utility companies;*
- *Utility companies are required to co-operate in that co-ordination process"*

Local authorities are obliged to keep a register of works in their area, including their own highway works. The street works undertakers have a duty to give notice of their intended (non-emergency) works, with traffic management plans, up to three months in advance. Undertakers not complying with the noticing requirements can be served with a fixed penalty notice under **The Street Works (Fixed Penalty) (England) Regulations 2007.**

The Traffic Management Act 2004 introduced a network management duty on local traffic authorities to manage their road networks to keep traffic moving. Traffic in this context means all highway users. The duty includes the coordination of activities on the network. This act also:

- *"necessitates co-operation with other authorities to help keep traffic moving on their networks;*
- *requires the appointment of a Traffic Manager by each authority;*
- *involves co-operation among different parts of an authority where their activities impact on the road network."*

The Street Works (Registers, Notices, Directions and Designations) (England) has two set of regulations (Similar legislation exists for Wales and Scotland):

i) **The Street Works (Registers, Notices, Directions and Designations) (England) Regulations 2007 (“Notices Regulations”)** sets out the regulatory regime for street works and in particular specifies the content of the register, how notices should be exchanged between street authorities and undertakers (e.g. gas, water, electricity and telecommunication companies) about planned or on-going works in a street, and the processes for either designating streets as 'protected', ‘special engineering difficulties' or as 'traffic-sensitive' or restricting further works by undertakers in a specific street.

ii) **The Street Works (Fixed Penalty) (England) Regulations 2008 ("FPN Regulations")** prescribes the form, manner of service and level of penalties for the fixed penalty notices that street authorities may give in relation to six offences specified in Schedule 4A to the New Roads and Street Works Act 1991 (“the 1991 Act”), as introduced by the Traffic Management Act 2004 (“the 2004 Act”). These offences are mainly associated with giving required notices about start of the works, completion of the reinstatement works, etc.

A significant feature of the notice regulations in the above statutes is the requirement for *the Electronic Transfer of Notices (ETON),* so that utility companies should provide certain information about the works they plan to carry out in advance through a standard electronic protocol. Such information can be used by decision support systems for a wide range of purposes such as estimation of delays, providing notices to the members of the public and travellers, and checking for possible clashes between proposed works.

2.5. Coordination of street works

2.5.1. Objectives and principles of street works coordination

The New Roads and Street Works Act 1991 requires street authorities to *coordinate* street works, with the aim of balancing the statutory rights of highway authorities and undertakers to carry out works with the right of road users to expect the minimum disruption from works (Department for Transport, 2012c).

The Government (Department for Transport, 2012c) believes that the efficient coordination of street works is one of the most important aspects of street works legislation, benefiting street authorities, undertakers and road users alike. The New Roads and Street Works Act 1991 (NRSWA) sets out the objectives of the coordination function:

- to ensure safety

- to minimise inconvenience to people using the street, including specific reference to people with a disability
- to protect the structure of the street and the apparatus in it

The function of the notice and coordination system is described as follows (Department for Transport, 2012c):

"The notice and coordination system balances the need to reduce the bureaucracy involved in managing street works with the importance of minimising delay and inconvenience to road users, whilst protecting the integrity of the street and any apparatus in it".

"This requires them to take a proactive approach to the management of the road network and the way authorities should tackle the causes of congestion and disruption."

Three pillars of coordination is defined for the coordination responsibilities of street authorities:

- **The Notice System:** Notices provide valuable information to aid the co-ordination process, while notice periods provide time for appropriate steps to be taken.
- **Streets subject to special controls:** Designation procedures allow for attention to be focussed on particularly sensitive streets. Traffic-sensitive streets are especially important in this context.
- **The Co-ordination Tools:** The legislation provides tools to help the co-ordination process, including powers to restrict further works following substantial street or road works and to direct the timing, date and location of street works.

The Department for Transport (2012c) has published a code of practice in order to help street authorities carry out their duty to coordinate works in the highway under section 59 of NRSWA, and undertakers to fulfil their duty to cooperate in this process under section 60 of NRSWA.

Street authorities and undertakers are required to adhere to three key principles in managing and undertaking street works:

- the need to balance the potentially conflicting interests of road users and undertakers' customers;

- the importance of co-operation and regular communication between street authorities and undertakers; and
- an acknowledgement that works programmes and practices may have to be adjusted to meet the statutory objectives of the coordination provisions.

For successful management and coordination of street works, the following key factors have been identified for the street authorities and undertakers (Department for Transport, 2012c):

- *"having shared objectives for completing work quickly, for minimising disruption and for exchanging information openly;*
- *talking to each other regularly – informally as well as formally;*
- *seeing others' perspectives and being prepared to be flexible for the overall good;*
- *facilitating decisions, e.g. by fielding people at planning meetings with the power to change things;*
- *dealing with problems promptly and collaboratively, and acting reasonably."*

In the UK, the Department for Transport (2008) has specified the following key principles which need to be adhered to for an effective coordination machinery of street works schemes:

- the sharing of information and consultation between interested parties at the earliest opportunity
- regular input and attendance of relevant people (those empowered to take decisions) at coordination meetings
- activity promoters and authorities sharing business development plans and replacement programmes for apparatus and highway assets with the coordinating authority
- communication of decisions at the earliest opportunity so that promoters plans can be adapted, if necessary
- cross-boundary co-ordination between neighbouring authorities, utilities, and others, especially for all planned works and planned maintenance on strategic routes

Similarly activity promoters (street works undertakers) have a responsibility to

- take part in early coordination
- consider joint working

- consider trench sharing
- highlight other activities which need to be coordinated with these activities
- produce reports for activity coordinators.

The aforementioned reference also highlights the fact that under the Traffic Management Act (2004), permit authorities must consider all aspects of the proposed activities and other influences that may affect traffic, including (but not limited to): “the optimum timing of activities from all aspects”.

Once the underlying objectives and principles relating to street works coordination are set out, the Department for Transport (2012a) describes a process for coordinating works on the street. This is explained in the following section.

2.5.2. The coordination process of street works schemes

To enable successful coordination of street works schemes, the following process has been prescribed for local authorities (Department for Transport, 2012c):

a) ***“Information****: The street authority needs accurate and timely information on what is proposed and when it is happening*

b) ***Analysis****: The street authority needs a means of assimilating and analysing this information. The street authority must consider whether any changes are required to minimise disruption before it agrees the proposals*

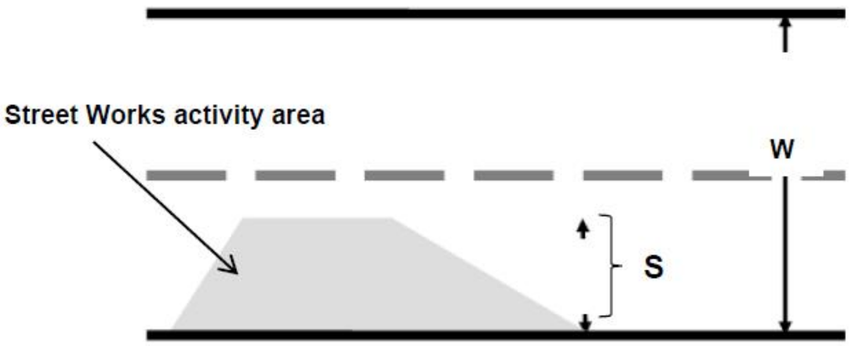
c) ***Consideration:*** *The street authority must consider whether any changes are required to minimise disruption before it agrees the proposals*

d) ***Cooperation****: All parties must co-operate with the street authority to achieve the minimum disruption”*

The Department for Transport (2012c) requires that, as part of the planning arrangements of street works, for each street work proposal a *disruption effect score* should be derived based upon the daily traffic flow of the road, carriageway width and the width of carriageway occupation as shown on Figure 2-5. The disruption effect score will then assist with an impact assessment of the proposed works which is extended to buses and pedestrians as well as the general traffic.

The disruption score deduced in this way, however, usually accounts for the local impacts of a street works scheme. Nonetheless the impacts of a link closure, including delays to the road users, are likely to propagate to other links of the network. As such, transport network studies which involve measuring the effect of link capacity degradation (e.g. work zone optimisation problems reviewed in section 6.2.1) use a traffic assignment model to capture the effects of road closures at the wider network level.

Factor	Description
[P]	The daily traffic flow, measured as an average am/pm peak hour flow in PCUs per hour, so that it takes account of HGV percentages. Source: Highway authority
[W]	The total width in metres of the carriageway (or the width of both carriageways for a dual carriageway road). Source: Ordnance Survey mapping using GIS tools
[S]	The width in metres of the activity occupying the carriageway, or in the case of activities on the footway, this would be the width in metres of the carriageway occupied by attendant vehicles and associated traffic management, as well as the width needed for any incursion of pedestrians, cyclists and horse riders into the carriageway. Source: Established as part of the works planning process



G.2 Calculation of Disruption Effect Score

The following algorithm is used to calculate the Disruption Effect Score:

Disruption Effect Score = [(P x100)/(1600x(W-S)/3.65)]

Figure 2-5 Derivation of “Disruption Effect Score” (Department for Transport, 2012c)

NRSWA requires that during the planning procedures attention must be focused on particularly sensitive streets, including (Department for Transport, 2012c; p. 93)

- Protected streets
- Streets with special engineering difficulties
- Traffic sensitive streets

A **protected street** is briefly defined as *“… any street that serves specific strategic traffic needs and therefore needs to be protected from unnecessary excavation and works …”*

The term ‘**special engineering difficulties (SED)**’ is attributed to *“…streets or parts of streets associated with structures, or streets of extraordinary construction, where* *works must be carefully planned and executed to avoid damage to, or failure of, the street itself or the associated structures, with attendant danger to person or property."*

Traffic sensitive streets are identified as having one or more of the following nine criteria:

(a) The street is one on which, at any time, the street authority estimates traffic flow to be greater than 500 vehicles per hour, per lane of carriageway, excluding bus or cycle lanes.

(b) The street is a single carriageway two-way road, the carriageway of which is less than 6.5 metres wide, having a total traffic flow in both directions of not less than 600 vehicles per hour.

(c) The street falls within a congestion charges area.

(d) Traffic flow contains more than 25% heavy commercial vehicles.

(e) The street carries more than eight buses an hour.

(f) The street is designated by the street authority for pre-salting, as part of its programme of winter maintenance.

(g) The street is within 100 metres of a critical signalised junction, gyratory or roundabout system.

(h) The street, or that part of a street, has a pedestrian flow rate in both directions at any time, of at least 1,300 persons per hour, per metre width of footway.

(i) The street is on a tourist route or within an area where international, national, or significant major local events take place.

The above categories of streets are subject to *special controls*, for instance in terms of whether to allow the undertakers' apparatus to be placed on these streets, in order to minimise disruption to the members of the public.

NRSWA provides a categorisation framework for street works activities, mainly based on the duration of the works, including ***major activities*****, standard activities, minor activities** and **immediate activities** (also called **emergency activities**)**.** These categories of works (defined in Department for Transport, 2012c; pp. 52-53) are associated with different notice periods which need to be given to the highway authority before start of the works. From the groups mentioned here, only *immediate* or *emergency* activities can be carried out with no or very little advance notice, thus eliminating opportunities for impact assessment studies and scheduling exercises.

Immediate works are either *emergency works* or *urgent works* as defined in the Street Works (Registers, Notices, Directions and Designations) (England) Regulations 2007:

Emergency works are defined in section 52 of NRSWA as "… works whose execution at the time when they are executed is required in order to put an end to, or to prevent the occurrence of, circumstances then existing or imminent (or which the person responsible for the works believes on reasonable grounds to be existing or imminent) which are likely to cause danger to persons or property."

Urgent works means:

(a) street works, other than emergency works, whose execution at the time when they are executed is required (or which the person responsible for the works believes on reasonable grounds to be required):

i. to prevent or put an end to an unplanned interruption of any supply or service provided by an undertaker;

ii. to avoid substantial loss to an undertaker in relation to an existing service; or

iii. to reconnect supplies or services where an undertaker would be under a civil or criminal liability if the reconnection is delayed until after the expiration of the appropriate notice period; and

(b) includes works which cannot reasonably be severed from such works.

If some remedial or reinstatement of parts of the immediate or emergency works can be carried out at a later stage, then the opportunity of planning these works arises again. Furthermore for some streets, generic contingency plans may be devised in advance for undertaking street works.

2.5.3. Examples of local authorities' practice on managing street works

Local authorities have been using various systems and arrangements in order to improve their performance in the management and coordination of street works schemes. A number of significant examples include:

- Almost all local authorities hold regular consultation and coordination meetings which are attended by representatives of utility companies and the relevant council(s) to discuss various aspects of the planned works, and identify and resolve any potential issues (e.g. conflicts, type of traffic managements, reinstatement needs) in advance.
- Essex County Council periodically distributes a spreadsheet among the stakeholders, containing the list and details (location, date and time, a point of contact, etc.) of all utility works planned across the county. They also issue an

internal publication at least once a year, containing the updated contact details of all utility companies which have utilities in Essex.

- The underlying details of all street works in London (location, timing, duration, undertaker names, etc.) have been made accessible to the stakeholders and members of the public through a web portal which is accessible on the internet (Transport for London, 2014).
- Many councils such as Bracknell Forest and Northumberland Councils have adopted street works software (Rothwell, 2014) in order to improve various aspects of street works management such as handling the street works register and the National Street Gazetteer database, inspections management, and defect reporting.
- Kirklees Metropolitan Council uses a scheme management database, namely the Highway Information Management System (HIMS), where all planned works for all undertakers are stored. The system produces clash reports, in which it becomes clear if two or more works could conflict. These reports are then used at coordination meetings to highlight potential conflicts, therefore enabling them to be resolved. The information is also used on a day-to-day basis before extensions are granted to any works, and to improve the management of the procedure for over-running works and minimising disruption (Department for Transport, 2007)
- Research and development activities are taking place on vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communication systems (e.g. see RITA, 2014) which can provide a range of envisaged benefits to the users of traffic networks, including giving first-hand and real time information to the drivers about the relevant road works on a highway network, and providing necessary directions to mitigate the adverse effects (hazards, delays, and so on.)

Efforts to develop the current procedures and tools used for coordination of street works are ongoing, since the Government and the public believe that there are still genuine opportunities for reducing delays, disruption and safety concerns associated with street works. In particular, no model has yet been developed to *collaboratively optimise* all underlying decision variables associated with planning the street works schemes within a traffic network.

2.6. Chapter concluding remarks

The practice of street works in the United Kingdom, including the relevant legislation and codes of practice, were reviewed in this chapter. This was preceded by looking into the issues and costs arising from undertaking a huge number of street works in the country every year in order to maintain the vital utilities and highway infrastructure for residents and businesses.

The coordination of street works schemes was highlighted in this chapter as a vital means of minimising the costs and disruption caused to society due to undertaking street works activities. Some Government legislation and codes of practice publications, explicitly or implicitly, encourage local authorities to try to *optimise* the underlying features of street works schemes for which they receive permit applications, not least the timing of the works and the layout of the areas on the roads which should be temporarily closed to the road users.

Currently, most councils use a range of procedures and tools to help them with managing street works in their networks. Such tools and procedures, however, lack a model which can help with identifying the optimum values of the decision variables which are associated with all street works schemes in a network in a collaborative manner.

Chapter 3
Literature Review

In order to achieve the objectives of this research, it has been necessary to conduct a literature review on several fundamental subjects in transport studies which are concerned with the assessment of traffic networks, particularly when a network is subject to disruptive events. This was in order to identify the underlying themes (e.g. concepts, assessment tools, solution algorithms, etc.) which can contribute to the development of the optimisation model of this study and its solution algorithm.

The chapter starts with the study of traffic assignment models, and continues with reviewing reliability, vulnerability and accessibility studies of traffic networks. Finally network design problem studies are reviewed.

3.1. Traffic assignment models

3.1.1. Introduction

The traffic assignment problem is concerned with predicting the route choices of travellers on road networks under a user equilibrium principle. A traffic assignment *model* is usually attributed to the formulation of a traffic assignment problem, together with devising a suitable solution algorithm for it.

Most traffic assignment models have been based on Wardrop's first principle (1952), as worded below, in order to model the flows on the links of a network, given the input data of the network such as physical road network, travel time flow function for each link, and trip demands (Watling, 2009a).

For each origin-destination pair at user equilibrium, travel times - or more generally generalised costs - on all used routes are equal, and less than or equal to that on any unused path.

An alternative concept of equilibrium associates with Wardrop's second principle, also called *the system optimum principle*:

In a system optimum, drivers are on routes such that the total travel time across the whole network is a minimum.

Compared with Wardrop's first principle, Wardrop's second principle has a very limited scope for application. This is due to the fact that it requires all network travellers to have the willingness and route knowledge necessary to minimise the whole network travel time.

Instead of the shortest paths (in terms of travel times) or the cheapest paths (in terms of travellers' generalised costs) a wide range of other concepts for the most *reasonable*, also known as *absorbing* or *preferred* paths (e.g. the most scenic or the least polluted paths), have been used in the literature (see Ghataee and Hashemi, 2009b). Many studies (e.g. Goodwin et al., 1998) support the concept of elastic demand – first formulated by Beckmann (1956) – which takes into consideration the (inverse) relationship between travel demand and generalised cost of travel in a network. As a result the basic user equilibrium is extended with the additional condition that for each origin-destination pair, the origin-destination travel cost and origin-destination trip demand should satisfy the demand function (Watling, 2009b).

Since their introduction, Wardrop's principles have been generalised in many ways in order to suit more circumstances in the real world. In the following sections, an overview of the most significant themes of traffic assignment studies are provided.

3.1.2. Multi-class user equilibrium

Zhang and Chen (2010) explain that in the classic traffic assignment problem, a single class of users is assigned routes in a network in order to fulfil a given travel demand. However the use of one class of users clearly introduces some limitations, for instance if one wishes to model urban networks, multi-modal networks, or multiple vehicle types. In multi-class traffic assignment models - first introduced by Van Vuren and Watling (1991) - there are multiple classes of users which have different cost functions. Users of different classes are assigned to the road network simultaneously. Each user will try to decrease his or her travel cost by changing routes until an equilibrium is reached where no one wants to change his or her choice because each user has chosen a route with the lowest cost.

Chen et al. (2011) mention two major applications of multi-class users in road networks: In the first application, the flows in a road network can be divided into different types of vehicles such as private cars, trucks and public transit. Each class of vehicles can have its own equivalent passenger car unit with different effects on travel times. In the second application, all road users are assumed to use the same type of vehicles but they are distinguished from each other in unobservable ways such as different values of time.

3.1.3. User equilibrium with stochastic and fuzzy parameters

In stochastic user equilibrium (Daganzo and Sheffi, 1977), the travellers' perception of travel time (or other underlying parameters related to route choice) is assumed to follow a random distribution. Two well-known variants of such route choice models are:

- **Multinomial logit model:** Travellers use a utility function to choose the preferred travel routes. The utility function consists of a deterministic component (to account for observed attributes of a choice e.g. travel time), and a random component (to account for unobserved attributes and errors), with the latter component following a Gumbel distribution (Sheffi, 1985).
- **Multinomial probit model:** This model is based on the assumption that the perceived travel time on each link is distributed according to a normal distribution function (Sheffi, 1985).
- **Fuzzy variants of the stochastic user equilibrium** (Teodorovic and Kikuchi, 1990):

Fuzzy models can complement or sometimes replace the stochastic variants of the traffic assignment problem in *uncertainty modelling* since they provide some advantages over the (purely) stochastic instruments, such as the ease of solving a fuzzy mathematical programming problem (Inuiguchi and Ramik, 2000). Furthermore the stochastic assumption for some underlying parameters of a traffic assignment model – as opposed to a fuzzy approach - can be unreasonable in many situations (Wen and Iwamura, 2008).

Ghataee and Hashemi (2009a) highlighted the three uncertainty sources in relation to traffic assignment models, as listed below, and subsequently developed a traffic assignment model with fuzzy level of travel demand, assuming the travel costs of links are dependent on their congestion.

- Inexact travel cost (a network with fuzzy travel cost)
- Unsure network topology (a network with fuzzy nodes and fuzzy links)
- Imprecise travel demand (a network with fuzzy excess node or deficit node)

Further discussion about the advantages of fuzzy theory have been provided in chapter 5 in relation to devising the objective functions of the optimisation model of this study.

3.1.4. User equilibrium incorporating travel time reliability

A statistical analysis undertaken by Abdel-Aty et al., (1995) identified ‘travel time reliability’ besides travel time and monetary travel costs as the most important criterion influencing route choice behaviour. Georgiou (1995) highlights the fact that the experience of the travelling conditions, not least any unreliability issues, is likely to cause travellers to change their routes in the following days. This is while most of the traditional traffic assignment models used for highway network planning focus on predicting *average* network conditions, and need to be modified or extended to deal with issues of unreliability (Watling 2009c).

There are many approaches which take into consideration the effect of journey time variability – associated with the reliability of the routes - on drivers' choice of route. One approach involves the incorporation of a measure of unreliability into the generalised cost of travel. Two common methods are:

- **Reliability Ratio (RR) method:** The generalised cost for each link is calculated as follows:

  $\mathbf{c = a\mu + b\sigma}$ (Eq 3.1) where:

  c = generalised cost (£)

  μ = travel time mean (mins)

  σ = travel time standard deviation (mins)

  a = value of time (£/min)

  b = value of travel time standard deviation (£/min)

  where the Reliability Ratio is defined as:

  RR = b /a

For a traffic network, σ is attributed to the highway *journey time variability* (JTV), and should normally be obtained by undertaking empirical studies. For instance, a study commissioned by the Department for Transport (2001) suggests that JTV in London roads can be modelled as a function of free flow travel time and the level of congestion:

$\sigma = 0.92\ T\ 0.87\ (CI - 1)$ (Eq 3.2)
where σ = standard deviation of travel time (seconds)
T = free flow travel time (seconds)
CI = congestion index (= t/T)
t = mean travel time (seconds)

- **Scheduling method:** This relates to the late arrival penalty user equilibrium (Watling, 2006):

  c = aμ + b' {Average Lateness} (Eq 3.3) where:

  c = generalised cost (£)

  μ = travel time mean (mins)

  a = value of time (£/min)

b' = value of one minute of lateness (£/min)

A 'Lateness Ratio' (LR) is defined as part of this approach as:

LR = b' / a .

Let τ = longest acceptable travel time (to avoid being late)

then

Average lateness = Average of all travel times > τ

Another approach for incorporating travel time reliability into the traffic assignment models is the *travel time budget model* of Lo et al. (2006) which is a multi-user class equilibrium model that considers both the expected travel time $E(T_k)$ and the variability of travel time, as measured by σ_{T_k},with users in class *m* minimising their travel time budget $B_k = E(T_k) + \lambda_m \sigma_{T_k}$ (Eq 3.4)

$\lambda_m$is related to the probability ρ_m that a trip arrives with the travel time budget

Many other travel time reliability models have been reviewed by Wang et al. (2013) where they also developed their own bi-objective user equilibrium model; it assumes that travellers always want to: 1) minimise the expected travel time; and 2) maximise travel time reliability. The underlying user equilibrium concept in their model which has incorporated travel time reliability is worded as:

"Under travel time budget bi-objective user equilibrium conditions, traffic arranges itself in such a way that no individual trip maker can improve either his/her expected travel time or travel time budget or both without worsening the other objective by unilaterally switching routes."

3.1.5. Adapting traffic assignment models for degraded network conditions

Ng and Waller (2010) highlighted the fact that transportation network reliability assessments are characterised by studying and modelling the behaviour of travellers under uncertainty. In addition to the models mentioned in the previous section, a number of other significant approaches can be found in the literature which have used different underlying assumptions as to how travellers behave under uncertainty and/or once they are faced with some routes being blocked during their journeys:

Non-adaptive behaviour: this is associated with the assumption that travellers exhibit Non-Adaptive behaviour, i.e. they do not change their paths as a function of the unfolding scenario. One motivation for such behaviour is that travellers simply do not have enough time to react because of the unpredictability of events (Clark and Watling, 2005). Another argument for this approach, as noted by Lo and Tung (2003), is that people have learned about the possible scenarios, based on which they have settled in a single, fixed, long-term equilibrium pattern accounting for the uncertainties. The former authors conclude that an immediate consequence of the non-adaptability assumption is that only a single, representative run of traffic assignment (e.g. based on some nominal levels of demand and capacity) is needed to predict travel patterns.

Partial-adaptive behaviour: This approach hypothesises that only the travellers on affected routes (i.e. routes whose capacities have decreased) have the ability to change their paths while travelling. Sumalee and Watling (2003) have termed the equilibrium state corresponding to the behaviour underlying this type of partial adaptability as Partial User Equilibrium (PUE). Under PUE, it is supposed that only a pre-defined subset of users in the network can realise the degraded condition of the network (i.e. 'the affected users'), and thus react to that change by diverting to alternative routes which is the case in real circumstances to a large degree. This is supported by many empirical studies, as noted by Noland and Polak (2002), which have shown that many travellers are even unaware of *planned* delays ahead of their journeys.

Fully-adaptive behaviour: This approach allows for fully adaptive behaviour, i.e. for every single scenario travellers decide on a new path to follow (e.g. Chen et al., 2002).

Clearly, there is still little consensus on travel behaviour under uncertainty. Various other network equilibrium models, adopting different behavioural assumptions, have been proposed in the literature (Yin and Ieda, 2001; Watling, 2002; Lo and Tung, 2003; Yin et al., 2004; Lo et al., 2006; Shao et al., 2006; Siu and Lo,2008; Szeto et al., 2006; Zhou and Chen, 2008; Lam et al., 2008; Ng and Waller, in preparation).

Detour models: When traffic assignment models are applied in order to forecast diversion rates at work zones, where the capacity of the links are partially or fully degraded, they may be referred to as detour models. A number of examples highlighted by Yang (2010, pp. 208-209) include:

- **System optimum detour model** which returns the optimal diversion rate that minimises the total delay on mainline and detour routes within each time unit. The system optimum diversion rates obtained from the SO model can provide control objectives for Intelligent Transportation System (ITS) in work zone sites.
- **Logit-based route choice model** borrowed from Song and Yin (2008) estimates diversion rates based on the difference of travel time on mainline and detour routes. The logit-based route choice model is more suitable for road users who are not familiar with the work zone situation and are quite sensitive to travel time information provided by Intelligent Transportation Systems (ITS).

- **User equilibrium model** obtains the diversion rate which minimises the difference in travel time between mainline and detour routes. The user equilibrium model is recommended for situations in which road users have relatively good knowledge of the road network and traffic conditions.

User equilibrium with recourse: Today many travellers are able to receive en-route traffic information during their journeys, and adapt their route choices during their journeys accordingly. This significant development has been the logic behind the *user equilibrium with recourse* model which was developed by Unnikrishnan and Waller (2009) with the underlying assumption that travellers receive information about uncertain network states as they traverse the network and make en-route routing decisions. In their model, the states of the network links are explained in one of a discrete set of states and follow a discrete probability distribution. These states can correspond to different operating conditions such as ‘normal operating state’, ‘the presence of a minor incident’, or ‘the presence of severe incidents’. The travellers are assumed to be unaware of the actual arc states when they depart from their origins: Only when a traveller reaches a node, does he or she observe the state of all of the arcs emanating from the node. The link states can be either correlated or independent, in the latter case travellers can receive further information about the downstream arc states by exploiting the correlation structure. Unnikrishnan and Waller apply the well-known Frank-Wolfe algorithm (1956) to solve the resulting convex optimisation problem.

When considering the fact that travellers can have access to en-route traffic information, Unnikrishnan and Lin (2012) showed that network design decisions (e.g. link capacity improvement schemes) are considerably different from those made when network travellers do not have access to such information.

3.1.6. Dynamic traffic assignment models

The notion of dynamic traffic assignment (DTA) is attributed to time-varying assignment of traffic flows in a network in order to explain *time-varying* route choice behaviours of travellers in various real word circumstances.

The DTA problem requires the user equilibrium principle to be expanded to cover each departure time individually instead of the entire analysis period, resulting in what is known as dynamic user equilibrium (DUE) (Chiu et al., 2011). As such, time dependent route choices for users leaving an origin are dependent on congestion levels caused by users who have an earlier, same, or later departure time. This requires an iterative process that, for most large networks, cannot be solved exactly and thus leads to a heuristic solution (Gemar, 2013).

DTA provides the ability to investigate hourly changes in traffic flow with the flexibility to analyse regional or corridor level travel behaviour. DTA models have recently become a practical option for modelling traffic as a supplement for existing static traffic assignment models. Users are assumed to modify their paths en-route based on prior experience, and the ability to anticipate future conditions in order to minimize their experienced travel time (Chiu et al., 2011).

Gemar (2013) explains that since the 1970's, researchers have been developing and improving methods for modelling time-variable travel behaviour in order to more adequately forecast how network flows change throughout a peak period or over the course of an entire day. These efforts have been made in response to the limitations of static traffic assignment models, which are unable to provide disaggregate, hour-to-hour flows and related travel times. The aforementioned author provides a list of characteristics pertaining to dynamic traffic assignment models, as provided below. However not all traffic assignment models which are known as being dynamic may necessarily possesses the entire set of these characteristics.

- Vehicles departing at different times are assigned different routes depending on conditions of the network (Chiu et al., 2011).
- Vehicles departing at the same time between the same O-D pair, but taking different routes, should have the same experienced travel time.
- Experienced travel time is only realized at the end of the trip (not at departure).
- Time-varying traffic flow conditions occur on the network (Peeta and Ziliaskopoulos, 2001).
- Randomness associated with traffic flow dynamics and human behaviour is incorporated.
- A universal or necessarily unique solution is not provided.
- Models are not characterized by standard mathematical properties.
- The process fosters both analytical and simulation-based approaches to solution methodology.
- Models are used to represent real-world characteristics of traffic flow.

Dynamic traffic assignment models entail development of traffic flow models and route assignment models suitable for time-varying conditions (a review is provided by Gemar, 2013; pp. 31-38).

DTA models can generally be classified into two categories: analytical models and simulation based models (Juran et al., 2009, quoted in Caggiani et al., 2012):

Gemer (2013) explains that simulation-based DTA models use a traffic simulator to generate traffic flows and represent real-world traffic dynamics (Carey and Subrahmanian, 2000; Peeta and Ziliaskopoulos, 2001) instead of utilising analytical evaluation to solve the DTA problem. This is to address flow propagation and spatio-temporal vehicle trajectories through simulation, due to the fact that mathematical formulations for these complex interactions are not readily available (Peeta and Ziliaskopoulos, 2001). The idea is to provide a solution that, although not derived analytically, is more meaningful from a practical standpoint. Since the simulator is used to determine the optimal solution, it should be noted that the network's level of detail has implications in terms of computational requirements (Gemar, 2013).

Simulation-based DTAs are based on sophisticated algorithms and detailed macroscopic, microscopic and mesoscopic traffic simulation techniques to estimate current network performance, predict future conditions and generate traffic guidance. (Caggiani et al., 2012). Several simulation-based mechanisms have been created and implemented, including iterative algorithms used to obtain both user equilibrium and system optimal solutions (Peeta and Ziliaskopoulos, 2001).

Dynamic traffic assignment models are usually embedded into traffic assignment software (see section 6.2.2) in order to evaluate a range of real-world application such as Advanced Traveller Information Systems (ATIS), and Advanced Traffic Management Systems (ATMS). Gemar (2013) mentions many DTA modelling works, such as:

- Development of a route guidance component for traffic management system in order to generate real-time and prediction-based guidance information for travellers (Ben-Akiva et al., 1997a); also developing a DTA model to measure the effectiveness of ATMS applications (Ben-Akiva et al., 1997b).
- Development of several DTA models to evaluate the effectiveness of ATIS tools which had been designed to provide route guidance information based on achieving system optimal status (Mahmassani and Peeta, 1993)
- Development of a DTA model to monitor and manage real-time ITS applications, including route guidance and ATMS (Florian et al., 2008)
- Development of a DTA model for the evaluation of construction impacts in the El Paso region in Texas (Pesti et al., 2010)

- Development of a series of DTA models to evaluate the impact of incidents on a portion of the Chicago network (Kamga et al., 2011)
- Development of a DTA model to assess the impact of incidents on network performance in order to evaluate the impedance of emergency response times due to resultant congestion (Sisiopiku and Cavusoglu, 2012)

Gemar (2013) notes that one of the key setbacks of using DTA analyses is that they can take a substantial time to build, properly calibrate, and complete. Moreover while DTA models offer more realistic results, they take a much longer computational time than ordinary (static) traffic assignment models. As such, expert judgement is required in order to establish whether the development and application of a DTA would be beneficial and cost effective for a real-world case.

Application of DTA models to understand the behaviour of traffic in relation to capacity degrading events (e.g. due to street works) can be quite beneficial or indeed sometimes essential, specially at congested traffic conditions, due to complexities arising from: the new layout of a link subject to traffic management schemes, behavioural response of travellers due to application of traveller information systems to alert and divert drivers approaching work zones, traffic restrictions on junctions, and so on. These conditions are often difficult or impossible to be modelled by static traffic assignment models, while they can sufficiently be analysed by simulated-based DTAs.

In practice, however, for many types of street works and highway maintenance schemes there is not sufficient time and budget for the application of DTAs. As such expert judgement should be used in order to predict the route choice behaviour of travellers, thereby allowing to calculate the amount of delays incurred by them during street works schemes. Since the majority of these schemes are planned to take place during off-peak traffic periods, traffic impact assessments without the application of DTAs are quite likely to produce realistic results.

3.1.7. Solution algorithms of the traffic assignment problem

The traffic assignment problem was first formulated as a convex optimisation problem with linear constraints by Beckmann et al. (1956). Since then, a significant number of algorithms have been developed to solve the original traffic assignment problem and its extended variants.

Traffic assignment algorithms are usually categorised by their fundamental approach in finding the traffic flows which satisfy the user equilibrium:

a) *link-based algorithm* dealing with link flow variables, such as Frank and Wolfe (1956), LeBlanc et al. (1975), MSA (Daganzo, 1982), and PARTAN (Florian et al., 1987)

b) path-based algorithms dealing with path-based variables, such as Marginal Cost Equilibration (Dafermos, 1971), Disaggregate Simplicial Decomposition (Larsson and Patriksson, 1992), and Gradient Projection method (Jayakrishnan et al., 1994)

c) *bush-based category algorithms* involving the construction of a sub-network (bush) during the optimisation process to find equilibrium flows: Xie et al. (2013) explain that link-based and path-based methods generally suffer from slow convergence behaviour. As such the past decade has witnessed the development and experiments of a class of bush-based algorithms (Bar-Gera, 2002; Dial, 2006; Nie, 2010; Bar-Gera, 2010; Gentile, 2012; Nie, 2012; Inoue and Maruyama, 2012; Boyles, 2012). These algorithms are a new focus in traffic assignment research since they promise to solve large-scale traffic assignment problems at a high level of precision and efficiency. Xie et al. (2013) consider the OBA algorithm developed by Bar-Gera (2012) and the LUCE algorithm developed by Gentile (2012) as the most favourable ones in this category.

It is worthwhile highlighting the fact that often, the solution algorithm developed for one type of traffic assignment problem can be easily modified – if not readily usable – to solve other types of traffic assignment problems. For instance Chen et al. (2011) mention that the three major types of solution algorithms for the traffic assignment problem can be easily modified for solving the user equilibrium problems with multi-class users. Also solving the elastic demand traffic assignment problem is possible by modifying a solution algorithm for the fixed demand traffic assignment problem: For instance Ryu et al. (2014) propose a modified path-based gradient projection method once the elastic demand traffic assignment problem is converted to a fixed demand problem through a modification of network representation.

In practice and for solving large and realistic traffic networks where a range of complementary models are required to analyse complex realistic network conditions (e.g. existence of traffic lights), traffic assignment packages are used to solve the traffic assignment problem (see section 6.2.2 for a review).

3.1.8. Concluding remarks on traffic assignment models

Traffic assignment models continue to be a major area of research in transport studies, and significant number of papers are published every year in order to improve or expand some aspects of the existing models. The importance of traffic assignment models partly stems from the fact that they are indispensable parts of other important assessment models in transport studies, such as network design problems, network vulnerability assessment methods, and work zone optimisation models which are reviewed in the following sections and chapters of this thesis.

By undertaking the review conducted in this chapter, it may be inferred that the decision on using what type of traffic assignment model can be particular to each individual case, dependent on a range of factors such as the trade-off between the cost and time of necessary data collection against expected accuracy of the model, ability of the model to incorporate the effect of capacity-degrading effects on the travellers, ability to incorporate the adaptive behaviour of drivers upon receiving traffic information en-route, ability to match or link with other types of network assessment models (e.g. traffic signals optimisation, simulation of traffic behaviour at junctions, ramp metering models, and so on). Usually those traffic assignment models which can take on-board more underlying factors are able to produce more accurate results; however they are more complex, more time-consuming to run, and require higher time and costs to obtain or collect the data they need.

The review on the traffic assignment problem in this chapter identified a range of models which are most suitable to analyse networks subject to journey time unreliability effects arising from road works. However due to the factors mentioned before, the scope of the present study excludes making a recommendation on a type of traffic assignment model which can be deemed most suitable for the assessment of traffic networks subject to the degrading effects of street works schemes. In fact, each case should be assessed in its own merits in order to select the most suitable and a feasible traffic assignment model, bearing in mind factors such as available information on the behaviour of travellers, level of required accuracy, and so on.

3.2. Reliability, vulnerability, and accessibility assessment of traffic networks

3.2.1. Introduction

Reliability, *vulnerability* and *accessibility* are fairly recent concepts in transportation studies, and are concerned with studying the condition and performance of traffic networks subject to disruptive events. These concepts are described in the following sections of this chapter.

3.2.2. Reliability of traffic networks

Reliability assessment of transport networks appears to have roots in the reliability studies of multi-state systems (MSS) which have a finite number of *performance rates* (i.e. intensity of task accomplishment) MSS are able to perform tasks with various performance rates, so that failures of elements only lead to the degradation of the system performance (Ding and Lisnianski, 2008). Multi-state reliability theories (see, for instance, Lisnianski and Levitin, 2003) can be utilised to estimate the reliability of a given system – normally explained by a probability distribution - based on the performance rates of the system components.

Clark and Watling (2005) report that network reliability is a relatively new concept which has been introduced to the studies of transport networks with an initial impetus derived from the study of major natural events affecting the connectivity of road network (e.g. Bell and Iida, 1997) such as earthquakes (Clark and Watling, 2005). Nevertheless apart from major infrequent events, reliability studies are also concerned with the impact of many frequently occurring events which could affect the operation of a network. These, for instance, can include minor accidents, on-street parking violations, snow, flooding, road maintenance and traffic signal failures, all of which would lead to variations in link capacities or free-run speed. In addition to the aforementioned causes, daily variations in activity patterns - manifested in varying traffic flow levels which are reflected in origin-destination trip matrix – can lead to varying level of network performance.

At the national level and with the ever increasing man-made and natural failure causes which threaten the infrastructural assets of the country, a high level of attention has been paid to increasing the resilience of assets – associated with the notion of *reliable infrastructure* - against potential failure causes. For example a ‘state of the nation’ report by the Institution of Civil Engineers (2009) highlighted the importance of maintaining reliable infrastructure networks across the country, and subsequently making several recommendations to the Government for enhancing the *resilience* of the infrastructural assets of the country for instance establishing a new single point of authority for infrastructure resilience).

From the transport planners' point of view, the importance of reliability assessment lies in the importance of predicting and understanding the performance of a network under various capacity degradation scenarios. Such capability has advantages over the reactive approach of modelling the existing situation once a link capacity is wiped out or degraded.

Clark and Watling (2005) noted that (in the future) network capacities, tolls or information sensors may be set with reliability consideration in mind. They proposed the application of an analytical approach for devising 'sensitivity analysis'-based algorithms for the assessment of transport networks. Nonetheless, it is acknowledged (Watling, 2008) that reliability is not just one issue, but a variety of issues, and the correct reliability analysis methods to adopt are likely to depend on the perspectives/objectives of the planners and policy makers.

The benefits of having appropriate reliability assessment models lie in the ability to direct both the design (Asakura et al., 2001) and economic appraisal (Du and Nicholson, 1997) of transport policy measures towards an improved treatment of such uncertainty (Clark and Watling, 2005).

Network reliability assessment techniques have been divided into several major classes (e.g. Clark and Watling, 2005; Ng and Waller, 2010), including:

Connectivity or terminal reliability (Wakabayashi and Iida, 1992; Bell and Iida, 1997; Asakura et al., 2003). This type of study examines the probability that specific origin–destination pairs in a network remain connected when links are subject to complete failures. Ng and Waller (2010) commented that because of the binary character of the link performance (they are either in service or not, or more generally, provide an acceptable level of service or not), connectivity reliability tends to be more appropriate for extreme events (e.g. earth-quakes). Moreover, these models tend to ignore congestion effects which are particularly relevant from a transportation planning perspective.

Travel time reliability (or **journey time reliability)** relates to the probability that travel times remain below acceptable levels. The Department for Transport considers journey time reliability an important part of evaluation studies of road schemes in its WebTAG guidelines (2009e), where it defines reliability as *"variation in journey times that drivers are unable to predict"*. This definition therefore confining the coverage of journey time reliability to random effects by excluding predictable variation relating to varying levels of demand by time of day, day of week, and seasonal effects which travellers are assumed to be aware of. In this context, unreliability issues arise from either variability in recurrent congestion at the same period each day, day-to-day variability, or variability in non-recurrent congestion such as incidents.

Ng and Waller (2010) note that the earliest journey time reliability studies used extensive computer simulation to determine the reliability of travel times (e.g. Asakura and Kashiwadani,1991), while later studies employed sensitivity analysis to reduce the computational burden (Du and Nicholson, 1997; Bellet al., 1999). In an attempt to further improve on the computational efficiency, Sumalee and Watling (2003) proposed an approach to obtain bounds on the reliability by only considering a subset of all possible scenarios. However, as the authors have noted, the approximation scheme is efficient only in situations where a large fraction of the probability mass is concentrated on a relatively small number of scenarios. The same authors later proposed a novel approach based on sample space partitioning to obtain bounds on the reliability of travel time (Sumalee and Watling, 2008).

Capacity reliability was introduced by Chen et al. (1999), and is defined as the probability that the transportation system can accommodate a given demand level at an acceptable level of service. A comprehensive simulation-based framework to assess this particular form of reliability was presented and discussed in Chen et al. (2002). More recently, Sumalee and Kurauchi (2006) used the concept of capacity reliability to evaluate network reliability in the wake of a major disaster.

Ng and Waller (2010) noted that in the current literature, the sources of uncertainty in a transportation network are often categorised as **demand uncertainty** (e.g. Asakura and Kashiwadani, 1991; Waller et al., 2001; Clark and Watling, 2005; Sumalee and Kurauchi, 2006; Lam et al., 2008), or **capacity uncertainty** (e.g. Wakabayashi and Iida, 1992; Chen et al., 2002; Sumalee and Watling, 2003; Sumalee and Watling, 2008).

In addition to the majority of the above studies which encompass the assumption of statistical independence for the failure causes, a few studies have attempted to relax this assumption. For instance, by postulating a multivariate normal distribution for the link flows in a network, Clark and Watling (2005) were able to model dependencies in link flows. Sumalee and Watling (2003, 2008) used a cause-based failure framework to introduce correlations in the capacity degradations.

Clark and Watling (2005) mention two other classes of reliability as:

Behavioural reliability methods are closely related with journey time reliability studies, and are concerned with how to represent, in an equilibrium framework, the impact on the typical route choice pattern due to the travellers being faced with unreliability issues during their journeys. This was reviewed before in sections 3.1.4 to 3.1.6.

Potential reliability which is concerned with vulnerability assessment of transport networks and are reviewed in section 3.2.3.

Travel time reliability studies have enhanced traffic assignment models so that they can incorporate travellers' behaviour during unreliable journeys too (rather than solely ordinary traffic conditions). Therefore these studies have indirectly contributed to those transport models which are concerned with optimising network configurations and planning transport investment schemes (e.g. network design problem studies introduced in section 3.3, and work zone optimisation problem studies introduced in chapter 6). However a few transport network studies have used maximising travel time reliability as the main objective of their entire optimisation models. This includes the work by Sumalee et al. (2006) which first introduced *the reliable network design problem.* Another example is the recent network design problem study by Sun et al. (2014) which set minimising the cumulative amount of a travel time reliability measure for network origin-destinations as the objective of their model in optimising road capacity expansion schemes of a network. The reliability measure they used, developed by Xu (2006), associates with the probability of the minimum actual travel time between a given origin-destination being less than a predefined threshold for that origin-destination.

In the context of evaluating highway construction and maintenance works, the term reliability assessment may refer to studying a broad range of effects arising from disruptive construction and maintenance activities upon relevant road users and communities. For instance during the author's experience of working as a highways engineer on the maintenance of the trunk road - under the Managing Agent Contractor (MAC) contracts with the Highways Agency - a requirement for the design studies was to produce a 'journey time reliability report' for every highway improvement scheme. This was in order to assess the impacts of the schemes, in relation to:

- The timing of the works in order to avoid pre-arranged events (festivals, sports events, etc.) as much as possible
- The proposed diversion routes in terms of:
    - Suitability for abnormal loads (i.e. vehicles with abnormal dimensions which can only run on certain types of roads such as motorways)
    - Increased travel time experienced by the diverted traffic

- Meeting the criteria for maximum length of the working areas and minimum distance between adjacent schemes as dictated by Chapter 8 of Traffic Signs Manual (Department for Transport, 2009f)
- Whether working during the so-called Public Service Agreement hours could be avoided whenever possible

For larger maintenance schemes, it is also a requirement under the Department for Transport's Transport Analysis Guidelines (WebTAG) to measure the equivalent monetary cost of the road users' costs, using the Department's QUADRO package (Department for Transport, 2014d). This package however does not take into account the network-wide impacts of the closures when journey times between many origin-destination centres change as a result of the imposed redistribution of traffic.

3.2.3. Vulnerability of traffic networks

3.2.3.1. Introduction

Jenelius et al. (2006) note that the concept of vulnerability can be divided into two parts, one containing the probability of a hazardous event and the other containing the consequences of the event in a certain place. Gilliard (2010) reports that the concept of network vulnerability in transportation studies dates back to the 1970s when it was first developed for disaster studies , and is highly related - although different - to network reliability studies: They argue that the concept of vulnerability is more strongly related to the **consequences** of link failure, for instance in terms of adverse social and economic impacts on the community (D'Este, 2007). On the other hand network reliability focuses on connectivity and probability.

Berdica (2002) suggested that the vulnerability analysis of transport networks should be regarded as an overall framework through which different transport studies could be conducted to determine how well a transport system would perform when exposed to different kinds and intensities of disturbances. Jenelius et al. (2006) proposed to use vulnerability study outputs for applications such as road management, prioritisation for road maintenance and repair (which is the very subject of this thesis), contingency planning, and for the assessment of regional disparities.

3.2.3.2. Classification of network vulnerability assessment methods

The review by El-Rashidy and Grant-Muller (2013) has identified a number of different vulnerability assessment methods in the literature (e.g. Jenelius (2009, 2010); Berdica (2002); Rashed and Weeks (2003); Taylor and Susilawati (2012); Brenkert and Malone (2005)) which arise from different interpretations of the concept of vulnerability and the scope of analysis. In general, however, two main methods exist:

a) methods based on use of a network-wide screen analysis (Jenelius et al., 2006): This approach gives a full analysis of the transport network by investigating the impact of closure of each link on the overall network performance; this impact is measured by the total network travel time. The main drawback of this approach is the high computational time required for a full network analysis. Chen et al. (2012) introduced an *impact area* vulnerability analysis approach based on the empirical findings that the closure of a link would mainly have serious impacts on its adjacent links and nodes within the local impact area. They showed that their proposed approach can significantly reduce the search space for determining the most critical links in large-scale networks, thus substantially reducing the computational burden to undertake a network-wide vulnerability analysis.

b) methods based on pre-selection of potentially vulnerable links according to a set of criteria: These methods have been developed to address the concerns associated with the network-wide screen analysis approach, and originate from the work by Murray-Tuite and Mahmassani (2004) who introduced a bi-level approach based on game theory in order to identify the most critical links in the road transport network. They defined a *vulnerability link index* to measure the importance of a particular link to the connectivity of an origin–destination (OD) pair, then aggregated over all OD pairs to obtain a disruption link index.

A review by Knoop et al. (2012) has identified a list of selection criteria, associated with *vulnerability attributes* (also called *indicators*), in the literature (e.g. Tamminga et al., 2005; Tampère et al., 2007) for network links in order to have a direction in the search for the most vulnerable links. These criteria are based on some underlying parameters related to the properties and performance of the network links, such as 'flow to capacity' ratios, the length of the queues before junctions, and risk-prone links. Knoop et al. (2012) concluded that these attributes should be considered as complementary rather than singularly, because different criteria identified different links as the most vulnerable. They also recommended that still further research should be undertaken to develop new criteria in order to allow identifying vulnerable network links without the need to do a full network-wide vulnerability analysis.

3.2.3.3. Vulnerability attributes (indicators)

El-Rashidy and Grant-Muller (2014) note that different approaches in the vulnerability assessment literature could also be classified according to the vulnerability indicators used. For example Taylor and D'Este (2007) and Chen et al. (2012) used accessibility and network efficiency indicators as metrics of vulnerability to identify the wider socioeconomic consequences of link closure, while Scott et al. (2006) employed transport network performance indicators to identify the *most critical* or *most important* link in the road network. El-Rashidy and Grant-Muller (2014) note that overall, the use and applicability of each approach will be heavily dependent on the scope of the research.

According to Srinivasan (2002), a vulnerability assessment may include deterministic factors (such as network capacity), quantitative time-varying factors (such as traffic flow and speed), some qualitative measures (for example event type and expected consequences), plus some random factors. There is therefore a need to develop an index in such a way that it can take into account various attributes of vulnerability. In the vulnerability model developed by El-Rashidy and Grant-Muller (2014) to assess the vulnerability of a road transport network, several vulnerability attributes are selected from the literature (e.g. Srinivasan, 2002; Tampère et al., 2007), and then combined with relative weights to produce a single *vulnerability index* (see section 3.2.4). Two examples of such indicators are:

- VA_1 which reflects the link traffic flow in relation to link capacity, and is estimated by:

  $VA_1 = \frac{f_{am}^i}{1-\frac{f_{am}^i}{C_{am}}}$ (Eq 3.5) where f_{am}^i is the flow on link a during period time *i* for a travel mode *m*, and C_{am} is the capacity of link a for a travel mode *m*. As the flow f_{am}^i increases with respect to capacity C_{am}, the number of vehicles experiencing higher levels of delay will increase.

- VA_2 which identifies the direct impact of link flow with respect to link capacity as defined below:

  $VA_2 = \frac{f_{am}^i}{C_{am}}$ (Eq 3.6)

Ideally, as noted by El-Rashidy and Grant-Muller (2014), the set of vulnerability attributes for a vulnerability analysis exercise should be as complete as possible, capturing as many features as possible of the impact of link closures in reality. It should also be as orthogonal as possible, capturing different aspects with a minimum degree of duplication. According to Srinivasan (2002), several types of attributes may have a significant effect on link vulnerability and these could be classified into four main categories, namely; *network characteristics*, *traffic flow, threats, and neighbourhood attributes.* Network attributes could include characteristics such as road types and physical configuration, whilst traffic attributes could cover link capacity, flow and speed. Attributes concerning threats may include event types and their expected consequences, with neighbourhood attributes capturing the influence of adjacent subsystems such as land use and population.

3.2.3.4. Development of a single link vulnerability index

El-Rashidy and Grant-Muller explain that to develop a single measure for vulnerability based on more than one vulnerability attribute, three approaches have been proposed in the literature (Srinivasan, 2002):

1) The first approach is based on experts' opinions in ranking or weighting each attribute and then combining these attributes using a simple linear regression model. This model can be calibrated using observed or reported vulnerability ratings for various levels of the contributing factors.

2) In the second approach, a continuous vulnerability index is represented by a function that includes all the proposed attributes. The relative weights are derived according to the best fit between the model prediction and actual ratings. The vulnerability index is then compared against a set of ordered

thresholds that are estimated from empirical models. For example if the vulnerability index is below the first threshold then the vulnerability rate will be 1 or if it falls in the range between the first and second thresholds then the vulnerability rate will be 2. However, determining these thresholds in an accurate way is a significant challenge and much further research would be needed in order to establish the threshold values.

3) The third approach is based on operational experience whereby experts choose a set of weights for some attributes (such as spare capacity and flow) in order to evaluate vulnerability if a particular scheme is implemented. The main advantages of this approach compared with the previous two methods are simplicity and flexibility, however it may be difficult to obtain the necessary data in practice.

El-Rashidy and Grant-Muller (2014) note that most of the research on vulnerability measures and methodologies has focused on assessing the impact of link closure for a particular origin–destination or at link level, but has not referred to the link characteristics that lead to vulnerability. As such they extended the work of Tampère et al. (2007) by introducing a new network vulnerability index on the basis of link vulnerability attributes. Their vulnerability index can be used to measure the impact of disruptive events (e.g. man-made events such as accidents or natural events such as adverse weather conditions) on road transport network functionality. Their network vulnerability index is calculated using two different aggregation of vulnerability index values of network links: an aggregated vulnerability index based on physical characteristics, and an aggregated vulnerability index based on operational characteristics. The former uses link physical properties such as its length and number of lanes, whilst the latter reflects aspects of the network flow.

To combine the various vulnerability attributes adopted for their analysis into a vulnerability index, El-Rashidy and Grant-Muller (2014) developed a new method based on fuzzification, and employed an exhaustive search optimisation technique. They also adopted fuzzification, which is the process of converting a crisp quantity to a fuzzy one (Ross, 2005), to accommodate the complexity and uncertainty in traffic behaviour alongside randomised elements in both traffic data and the simulation process. In their study, each vulnerability attribute is evaluated according to four assessment levels represented by four fuzzy membership functions. An exhaustive search technique is then employed to identify the optimal weight contribution of each fuzzified attribute. They determined the optimal values by the level of weights at which the correlation between the vulnerability index and the given total travel cost is the strongest.

3.2.4. Accessibility of traffic networks

Accessibility is defined as the ease with which an individual can access services and facilities that he or she needs or desires (Department for Transport, 2004a). The accessibility concept encompasses the entire journey chain from the origin to destination and reflects the ability of individuals to reach and use transport and services and infrastructure.

Travel time and cost of travel are the most well-known factors impacting on accessibility; however accessibility is also influenced by a range of other factors such as location of facilities and services, methods and timing of service delivery, safe routes of travel, and fear of crime (Department for Transport, 2004a).

Accessibility assessment is now an important part of the appraisal and modelling studies for most highway and public transport improvement schemes in the United Kingdom.

Accessibility measures or indicators are used to quantify accessibility, and assess the ease with which an individual, population segment or community can access one or more services from a residential or other location using available modes of transport. Several types of indicators for measuring accessibility have been observed in the literature (see, e.g. Morris et al., 1979; Department for Transport, 2004a; Halden et al., 2005; Kilby and Smith). The most common ones, as reviewed by Department for Transport (2004a), include:

Access measures assess the ease of access to the public transport network i.e. from the home to the nearest appropriate bus stop or railway station. However they do not incorporate details of the public transport journey time, distance or cost.. An example of this type of indicator is "the proportion of the population having access to a bus service with a minimum frequency of four or more services per hour, from a bus stop situated within a 10-minute walk of their home".

Threshold measures have been introduced as the most commonly used accessibility measures which are applicable to all modes of transport; two examples of a threshold based accessibility indicator are: “the proportion or number of older people within a 10 minute walk of the nearest GP” or “the proportion or number of households with no access to car within £1.00 travel cost of their nearest hospital”.

Continuous measures are considered as the most robust form of accessibility measure as they encompass a range of characteristics and parameters to deduce a single value of accessibility for a given location. Several examples of these parameters and characteristics are: door-to-door travel time, characteristic of the facilities and services such as total number of available shops, a deterrence function to reflect the deterrent effect on likely travel of increasing time and cost, etc.

Composite measures of accessibility have been devised in order to provide a means of using two or more accessibility measures in combination, and provide a way of identifying locations and areas within an authority with the greatest combination of accessibility problems.

Comparative measures of accessibility are a means of using accessibility measures in combination and are usually expressed as accessibility ratios using pairs of access, threshold, continuous or composite measures. Comparative accessibility measures have been highlighted as being particularly useful for investigating disruptive impacts which is of particular interest to this study. The example provided is "the proportion of the pupils of compulsory school age in receipt of free school meals able to access their nearest school within 15 minutes, compared to equivalent value for all pupils of compulsory school age".

Qualitative measures of accessibility can be obtained by undertaking qualitative surveys, and are most useful for informing an accessibility assessment and in the development of potential solutions for an action plan. An example of qualitative measures is the response of the population to a survey on perception of crime, whereby responses can be one of the following: very safe, fairly safe, a bit unsafe and very unsafe.

Accessibility indicators can be used in transport investment studies (e.g. network design problem studies introduced in the following section) to evaluate some benefits of a given transport improvement scheme (road capacity improvement, highway maintenance works, etc.). However such benefits are difficult to be expressed in monetary terms in order to be embedded into the overall economic evaluation of such investment projects. Furthermore different accessibility indicators are needed to measure the accessibility of different groups of people to different types of facilities. Therefore the decision on selecting the appropriate type(s) of accessibility measures for incorporation into a transport investment evaluation model can be quite difficult (unless that scheme is targeted for improving certain types of accessibilities in advance). These issues, however, appear to have been addressed by using monetised hourly values for road users' travel time savings (or delays) in order to evaluate the benefits or adverse impacts of transport investment schemes.

Accessibility indicators, however, can be very useful to be used for defining appropriate constraints or requirements for transport investment models, for instance:

"no road closure due to the road works should result in increasing the travel time of the residents of an area to the local hospital twofold or more".

3.3. Network design problem studies

3.3.1. Introduction

Kim et al (2009) provides a definition for network design problem in the context of transportation networks as: *"a collection of models dealing with decision problems related to transportation infrastructure investment".* However due to the wide scope and variety of network design problem studies in the transportation sector and other disciplines such as communication, many other definitions have been proposed (e.g. Dantzig et al., 1979; Friesz, 1985; Magnanti and Wong, 1984; Farahani et al., 2013).

Generally, network design problem models are formulated in order to find the optimal network configuration at the planning horizon (Kim, 2007). They are concerned with developing and then solving a mathematical optimisation model with the aim of minimising or maximising one or more objective functions (see sections 3.3.3 and 3.3.4). The alternative and traditional approach of analysing each investment scheme in a network in isolation from other schemes, entailing the use of point estimates based on past trends, has been shown to result in sub-optimal decisions (Ukkusuri and Waller, 2006). Due to using inaccurate forecasts, schemes studied using the traditional point estimates approach are economically risk-prone, potentially leading to significant economic losses (e.g. Flyvbjerg et al., 2005)

Network design problem covers the planning, design and management decisions in relation to transport network improvement schemes, aiming at finding the optimal decision parameters in relation to: *a)*the objective(s) which has/have been set for the network and the investment projects; and b) the prevailing constraints and requirements. For instance: the problem of choosing the amount of spending on capacity improvement of some network links, from a range of available options, in order to minimise the total road users' travel times in the network, and subject to the available budget for road capacity improvement schemes.

Farahani et al. (2013) note that network design problem studies – sometimes referred to by the acronym TNDP (where *T* stands for transportation) or simply NDP - have been continuously studied within the last five decades in transportation studies, and also other disciplines such as communication networks. This has resulted in extensive number of publications, setting out various types of network design problem models and their associated solution algoorithms, because the problem is highly complicated, theoretically interesting, practically important and multi-disciplinary.

3.3.2. Classification of network design problems

Depending on the factors such as context, scope, type of decision parameters, and the underlying assumptions of a network design problem study, they may be classified into various different categories, and thereby are known by different acronyms. Several significant examples are:

- Urban Transportation Network Design Problem (UTNDP) which is concerned with optimising transport improvement schemes in urban networks (e.g. Miandoabchi and Farahani, 2011)
- Flexible Network Design Problem (FNDP) which is attributed to those network design problem models which generate optimum scheduling of capacity improvements within a multi-period time framework (e.g. Patil and Ukkusuri, 2009)
- Public Transport Network Design Scheduling Problem (PTNDSP) which is concerned with determining optimal transit routes, frequencies and time-tables (e.g. Curtin and Biba, 2011)
- Multi-Modal Network Design Problem (MMNDP) which is concerned with considering at least two transport modes (e.g. car and bus) in relation to optimising the decision variables of the model (e.g. Miandoabchi et al., 2012)
- Continuous (e.g. Wang and Lo, 2010), Discrete (e.g. Long et al., 2010), or Mixed (e.g. Gallo et al., 2010) Network Design Problems (CNDP, DNDP, MNDP) which entail, respectively, optimising decision variables which accept continuous values (e.g. the amount of tolls), discrete values (e.g. making some streets one way), or both types of values (e.g. street capacity expansion plus lane allocation in two way streets)

Network design problems can be grouped into *static*, in which stationary travel demand and infrastructure supply is assumed, or *dynamic*, for instance when a variable message sign is used to change the free speed and consequently the capacity of a link (Wismans et al. 2011b)

Stochastic network design problems are used when one or some variables of the model, such as origin destination demand values, are not known. In such circumstances the optimisation model will aim at optimising statistical measures such as the expected value of the underlying function (Waller & Ziliaskopoulos, 2001; Chen et al., 2010). In order to compute the stochastic functions of such problems, a Monte Carlo or stochastic simulation is performed which is based on sampling random variables from probability distributions to compute the stochastic functions (Liu 2009).

Miandoabchi and Farahani (2011) note that the underlying decisions which are subject to optimisation in transportation network design problem studies can be attributed to *strategic*, *tactical*, or *operational* level decisions (this was first proposed by Magnanti and Wong, 1984). For instance the strategic level decisions are concerned with the expansion or construction of network streets. Setting the street orientations is a tactical decision while setting the traffic lights is an operational level of decision. As such, most network configuration changes due to traffic management schemes for street works entail operational and tactical level decisions.

The scope of network design problem studies can sometimes go beyond optimum decision making on transport improvement schemes, for instance by concerning the location and travel demand level of the origins / destinations of the network too: One example is the facility location network design problem studies (e.g. Jabalameli et al., 2011), first introduced by Weber (1929), which deal with determining the optimal locations of facilities, i.e. origins / destinations of the network, and the design of the network links simultaneously.

3.3.3. General formulation of transport network design problems

Farahani et al. (2013) noted that transportation network design problems differ from network design problem in other industries such as communication, because the reaction of travellers has to be taken into account when designing a transportation network. Moreover designing a transport network is associated with certain transport policies which are reflected in the objective function(s) of the problems. They explain that a network design problem is usually formulated as a bi-level problem or a leader-follower problem, where:

- The upper level problem is the leader’s problem, the design problem, or the problem of the decision maker (e.g. the government) who plans or manages the transport network. This upper level problem is related to the policy discussion in practice and includes the measurable goal (e.g. reducing total road users’ travel time), restrictions (e.g. political, physical, and environmental constraints) and the design decisions to be made (e.g. new roads to be built). This upper level problem assumes that the leader can predict the behaviour of the travellers.
- The lower level problem is the followers’ problem or the problem of travellers who decide whether to travel, and if so, their travel modes and routes.

The bi-level structure allows the decision maker to consider the reaction of the travellers and improve the network to influence the travel choice of travellers, but has no direct control on their choice. However this structure does not allow the travellers to predict the decision of the leader, but only allows them to determine their choice after knowing the decision of the leader.

The mathematical representation of bi-level optimisation problems and their intrinsic characteristics in relation to finding suitable solution algorithms for them are discussed in chapter 6 where the optimisation problem of the present study is to be developed.

3.3.4. Objective functions of transportation network design problems

Miandoabchi and Farahani (2011) report that the majority of transportation network design problem stuides are based on the minimisation of total travel cost or travel time of users of the network (e.g. Friesz et al., 1993; Gao et al., 2007; Wang and Lo, 2010). However more recently maximising the *reserve capacity* of a network has been observed as the objective function in many network design problem studies (e.g. Chiou, 2008; Miandoabchi and Farahani, 2011; Ceylan and Bell, 2004). The concept of reserve capacity, which is defined as follows, was first suggested by Yang and Bell (1998), and then used by many other researchers later on:

“reserve capacity is the largest multiplier applied to a given existing demand matrix that can be allocated to a network without violating the arc capacities which depend on capacity constraints, (traffic signal) cycle times, green constraints and others”.

Yang and Bell (1998) identified several advantages of using ‘reserve capacity maximisation’ over the traditional travel time minimisation in certain circumstances, for instance when uncertainty exists in traffic demand.

A wide range of other objective functions have been used in the network design problem literature, such as:

- Minimum total vehicle miles (e.g. Friesz et al., 1993)
- Maximum consumer surplus (e.g. Yang, 1997)
- Maximising equity among the road users (e.g. Connors et al., 2005)
- Minimum construction cost plus network travel time (e.g. Xu et al., 2009)
- Maximum profit with road tolls setting (e.g. Dimitriou et al., 2008)
- Maximising network travel time reliability (e.g. Sun et al., 2014)

Chen et al. (2010) highlight the fact that the transportation network design problem is inherently multi-objective due to confronting the various needs of different stakeholders. This means that often increasing the value of one objective may entail reducing the value attained for one or more other objectives. A few examples include:

- minimising total travel time and maximising reserve capacity (Yang and Wang, 2002)
- minimising total travel time and maximising revenue (Yin, 2002)
- minimising total travel time of road users and minimising infrastructure cost of the government (Tzeng and Tsaur, 2010)
- maximising expected profit and minimising risk (variability of profit) of private investors in roadway projects (Chen et al., 2003)
- maximising expected profit of private investors and minimising expected inequity of road users in a build-operate-transfer project (Chen and Subprasom, 2007)

Multi-objective optimisation problems may not yield to a single optimum solution, depending on the solution methodology adopted, and therefore a range of optimum solutions may be produced for a given network design problem. Different approaches to solving multi-objective optimisation problems are reviewed in chapter 7.

Overall, the choice of what objective functions should be set for transport improvement schemes very much depends on the statutory responsibilities, policies and preferences of the relevant traffic authorities who sponsor the investment projects under question.

In practice, it appears that the economic benefits of road improvement schemes which encompass travel time savings (by using monetary rates for time-savings) continue to be the dominant objective for policy makers in many projects. Meanwhile attempts are made where possible to translate other benefits and impacts of road improvement scheme (e.g. safety and environmental gains) to equivalent monetary values.

In order to conduct cost benefit analysis of all impacts of transport networks In the UK, various appraisal techniques which are consistent with the Green Book (HM Treasury, 2014) are used (Department for Transport, 2012d). To bring these impacts to the same units for comparison, the Green Book (HM Treasury, 2014) requires that monetary valuations are applied, wherever possible, to convert the respective quantities into monetary values. For example, value of time rates are applied to convert the time savings calculated by transport models into a monetary value for time-savings.

Some of the valuations that are applied in transport appraisal can be taken directly from prices paid in markets, or predictions of prices in future markets e.g. fuel prices. Other valuations have been derived from research using techniques such as *hedonic pricing* (Rosen, 1974) and *stated preference* (e.g. the valuation of some noise impacts, and the value of travel time savings). Where valuations rely on research or experimental methods they are reviewed by experts to ensure that they are robust enough to be used in cost-benefit analysis. In chapter 5, the monetised impacts of street works schemes will be identified in order to be accounted for by the optimisation model of this study.

It is acknowledged that there are some other impacts where it is currently infeasible to derive a reliable monetary value for (Department for Transport, 2012d). However the fact that these impacts are not expressible as monetary values should not lead to the conclusion that they are neglected by the decision-maker. Instead they should be presented in a consistent form (e.g. in a matrix) that gives a clear sense of the severity of the impact even if the impact cannot be simply added or subtracted from the other impacts that have been expressed in units of money.

3.4. Chapter concluding remarks

In this chapter a number of key topics in relation to the analysis of transport networks, particular those subject to capacity degrading events, were reviewed.

The review started by studying traffic assignment models which are concerned with predicting the route choices of travellers on road networks under a user equilibrium principle. Among many different types of traffic assignment models available which have been developed over the years using different underlying assumptions about travellers' route choice behaviours and the concept of user equilibrium, a limited number are suitable for analysis of networks subject to journey time unreliability effects arising from road works (e.g. *user equilibrium with recourse* developed by Unnikrishnan and Waller, 2009). However it was concluded that the decision as to what type of traffic assignment model should be used may vary with each individual case, dependent on factors such as the trade-off between the cost and time of necessary data collection against expected accuracy of the model.

Next in this chapter, three closely related concepts, namely reliability, vulnerability, and accessibility of traffic networks were reviewed. These models - being intrinsically very diverse in terms of the scope and objectives of the studies - are concerned with studying traffic networks under degraded conditions in order to work out the underlying facts such as: the probability that the travellers between a network origin-destination can complete their journey in a certain time period, the consequence of certain links of the network becoming blocked (in terms of the effect on total network travel time), and measuring 'the ease of access for a certain group of people to reach some facilities using the available road network and transport facilities.

Many performance indicators which have been developed and used as part of these studies (e.g. to explain the relative importance of a given road of a network) are likely to be incorporated into network design type of studies as a valuable aid to making optimum decisions in relation to transport improvement schemes. Two examples are: measuring the importance of a given road relative to other network links; and rating the accessibility level of a destination point in a traffic network.

Finally network design problem studies were reviewed in this chapter. These studies entail formulating investment decision problems relating to a wide range of transport improvement schemes (road capacity improvements, traffic management regulations, service frequency of public transport systems, and so on) in a traffic network. It was revealed that network design problem models are normally formulated, in mathematical terms, as a bi-level optimisation problem, comprising an upper level problem (i.e. the design problem of the decision maker), and a lower level problem associated with the travel pattern of the road users in response to the decisions made by the decision maker.

As the optimisation problem of this study fits well within a generic network design problem formulation (this will be explained in chapter 6), further investigation into the characteristics of bi-level optimisation problems, particularly with respect to identifying suitable solution algorithm for them, has become necessary. Such complementary review will be undertaken in chapter 6 where the optimisation model of this study is developed.

Chapter 4
Research Completion Roadmap

4.1. Introduction

Instead of providing a single research methodology chapter in this thesis, the detailed methodologies which have been used to formulate the optimisation problem of this study, and the proposed algorithm for solving it are explained in chapters 5 to 7. This is because devising those methodologies form the main contribution that was required to meet the objectives of this research.

The aforementioned chapters, however, are preceded with the present one which describes a *roadmap* in order to guide this study towards achieving its objectives as set out in chapter 1. This roadmap represents the overall methodology which is adopted in this thesis to meet its objectives, and comprises several *work stages*, starting from the literature review up to undertaking experimental tests with the optimisation algorithm. The key themes of the work undertaken within each of these stages are briefly reviewed in the following sections of this chapter.

Before searching for any similar optimisation studies which can assist with developing the optimisation model of this study, a review was undertaken in chapter 2 to understand the key aspects of street works practice in urban networks. This led to identifying the objectives which have been set for practicing street works schemes, the key stakeholders, cost of street works schemes, and the necessary coordination activities for undertaking street works schemes. The review in chapter 2 revealed a UK Department for Transport publication (2012c) which specifically advocates *optimisation* of the *timing* of street works as a duty upon network authorities. By reviewing other transportation studies with similar characteristics such as network design problem models (section 3.3) and work zone optimisation models (section 6.2), It is well appreciated now, however, that there is often a wider scope for producing optimum schedules for street works schemes. In addition to the start time of each scheme, other decision variables such as the traffic management arrangements, the amount of resources allocated for undertaking a scheme, and the sequence of the links subject to each scheme can be subject to such an optimisation exercise.

This review identified the following stakeholders which are concerned with different aspects of street works activities, and are potentially affected during the implementation of the schemes:

- Road users affected by reducing the capacity of the network links.

- Local residents, businesses and public services that my suffer from reduced accessibility during street works.
- Transport network authorities who are responsible for maintenance of their highway networks, as well as ensuring that delays incurred by road travellers remain as low as they could possibly be.
- Street works undertakers and their customers who wish to have street works completed in the safest, quickest and cheapest way; this normally involves maximum level of space occupation during the works.

An optimisation model suitable for scheduling of street works schemes needs to take into consideration the objectives of the above stakeholders, which are associated with minimising the amount of costs and disruptions incurred by them during the implementation of the schemes (any benefits from street works schemes can be regarded as negative costs).

The literature review, however, has revealed a number of conflicting goals in relation to the stakeholders mentioned above, which are shown on Figure 4-1.

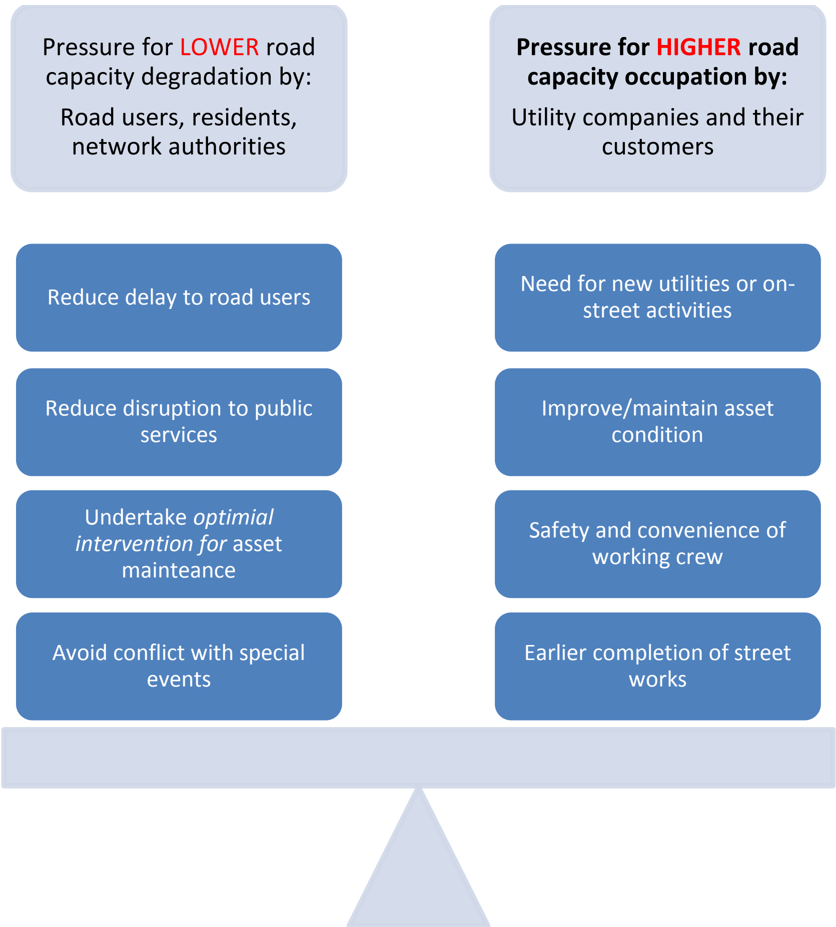


Figure 4-1 Conflicting goals associated with street works stakeholders

These conflicting goals may sometimes be expressed by the same stakeholders. For instance traffic network authorities are concerned with maintaining their traffic network assets in good condition by commissioning construction and maintenance works in the safest way, thus requiring more frequent works and higher space occupancy during the works. However they are also very keen to keep delays and disruptions as low as possible due to their statutory responsibilities of managing their traffic networks.

The literature review then continued by conducting an investigation into the following *themes* in the existing research literature:

a) transport studies which are concerned with studying traffic networks subject to degraded conditions

b) transport studies concerned with circumstances where a trade-off needs to be reached between the goals of different stakeholders who share the benefits of using a traffic network

The subjects identified as part of 'theme a' assisted with enabling the optimisation model of this study to *measure* the effects of street works schemes.

The investigation into 'theme b' led to finding several types of studies which are concerned with optimising different decision parameters of highways-related maintenance and improvement schemes. A common objective of these studies is to find the *optimal trade-off* between the conflicting objectives of the stakeholders, including the scheme undertakers and the network users.

The literature review identified many decision variables which may be subject to optimisation by the policy makers and network designers in various transportation-related optimisation models. These models are generally concerned with making optimal changes to the configuration of a transport network. A number of examples for such variables include: the length of a highway work zone, the type of traffic management for a link (e.g. one-way traffic management, total link closure, etc.), the level of increase in the capacity of the links, the sequence of the assets which need to be built or repaired, the locations and levels of tolls on roads, the timing of maintenance works, and so on. These models also take into account a range of other variables and constraints which are beyond the control of the network planner, such as the time-varying traffic levels in the network, annual available budget for improvement schemes, restrictions on degrading the capacity of links, and so on.

Figure 4-2 shows the most significant variables which are likely to be incorporated into a street works optimisation model, in two categories: The scheme related variables are those which can be subject to optimisation. The network related variables are normally outside the control of the street works planners.

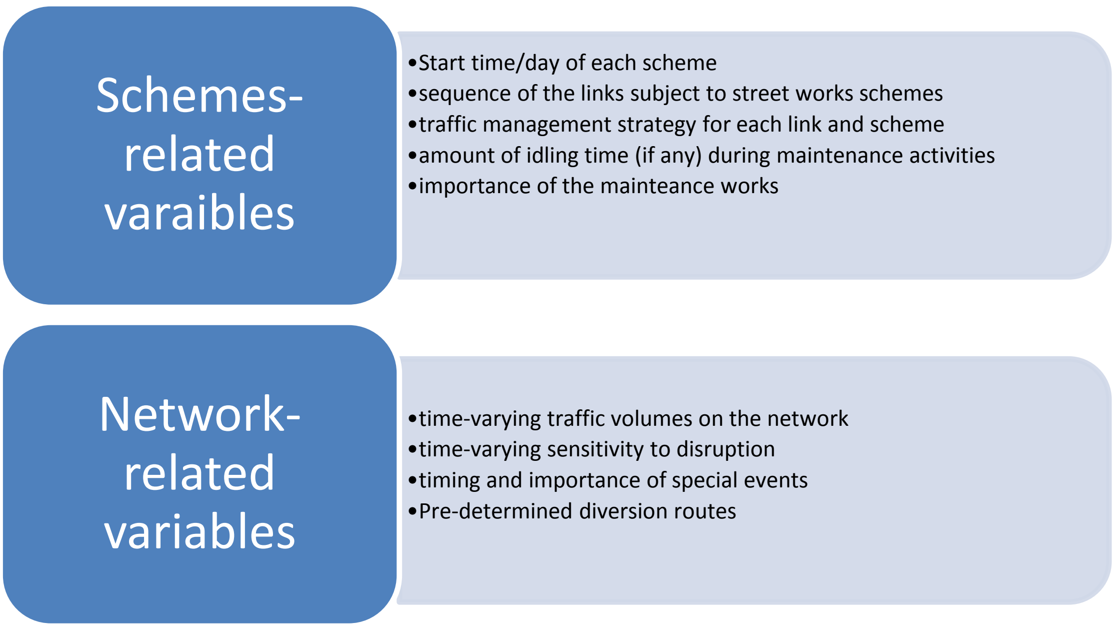


Figure 4-2 Identifying the underlying variables of the street works optimisation model

Figure 4-3 is a snapshot of the subjects which have been found relevant for literature review in this thesis in order to help with achieving its objectives. The overarching topics are specified on the left column, and the subjects covered for each topic are shown on the right column.

This study has borrowed at least four key themes from the subjects specified on Figure 4-3 in order to develop the optimisation model and its solution algorithm:

a) A *bi-level optimisation programming* formulation to express the optimisation model of this study in mathematical terms

b) Application of a traffic assignment model, tailored for degraded network conditions, in order to work out the delay costs incurred by travellers due to the implementation of street works activities

c) Adopting a *project scheduling formulation* in order to deduce the duration and costs of street works schemes within the optimisation model

d) Application of a suitable *meta-heuristic algorithm* for solving the optimisation problem of this study

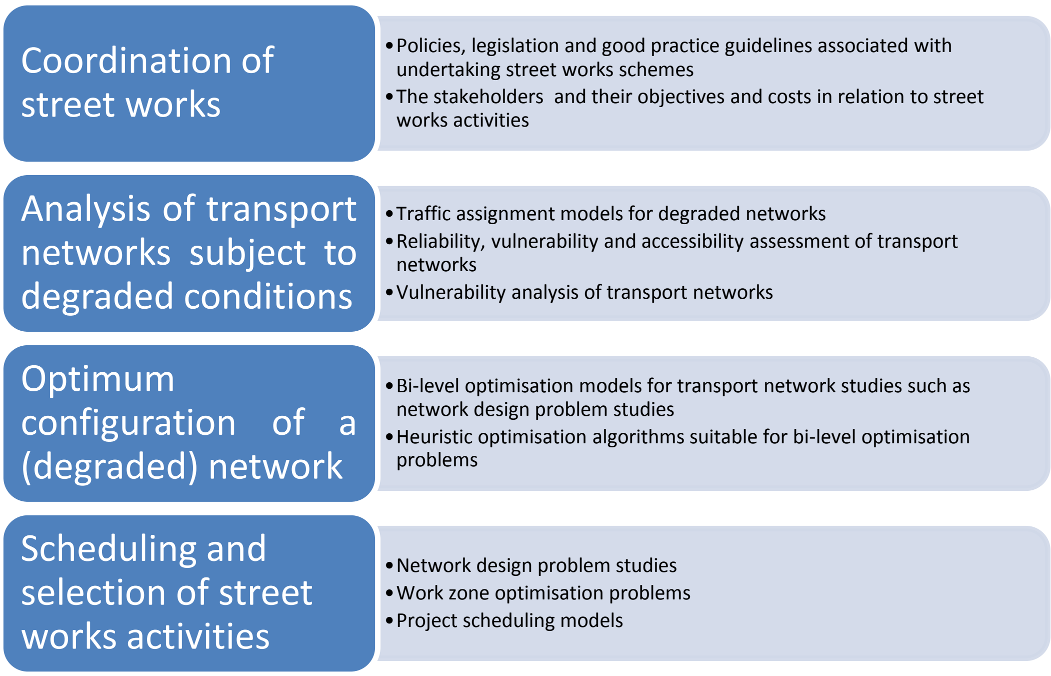


Figure 4-3 Relevant subjects for literature review

The overall findings of the literature review helped with devising a *roadmap* for completion of this thesis. This roadmap, as shown on Figure 4-4, comprises four main stages which need to be completed to ensure that the two objectives of this thesis can be achieved.

The following sections of this chapter describe how the goals set for each stage of the roadmap will be accomplished in this thesis.

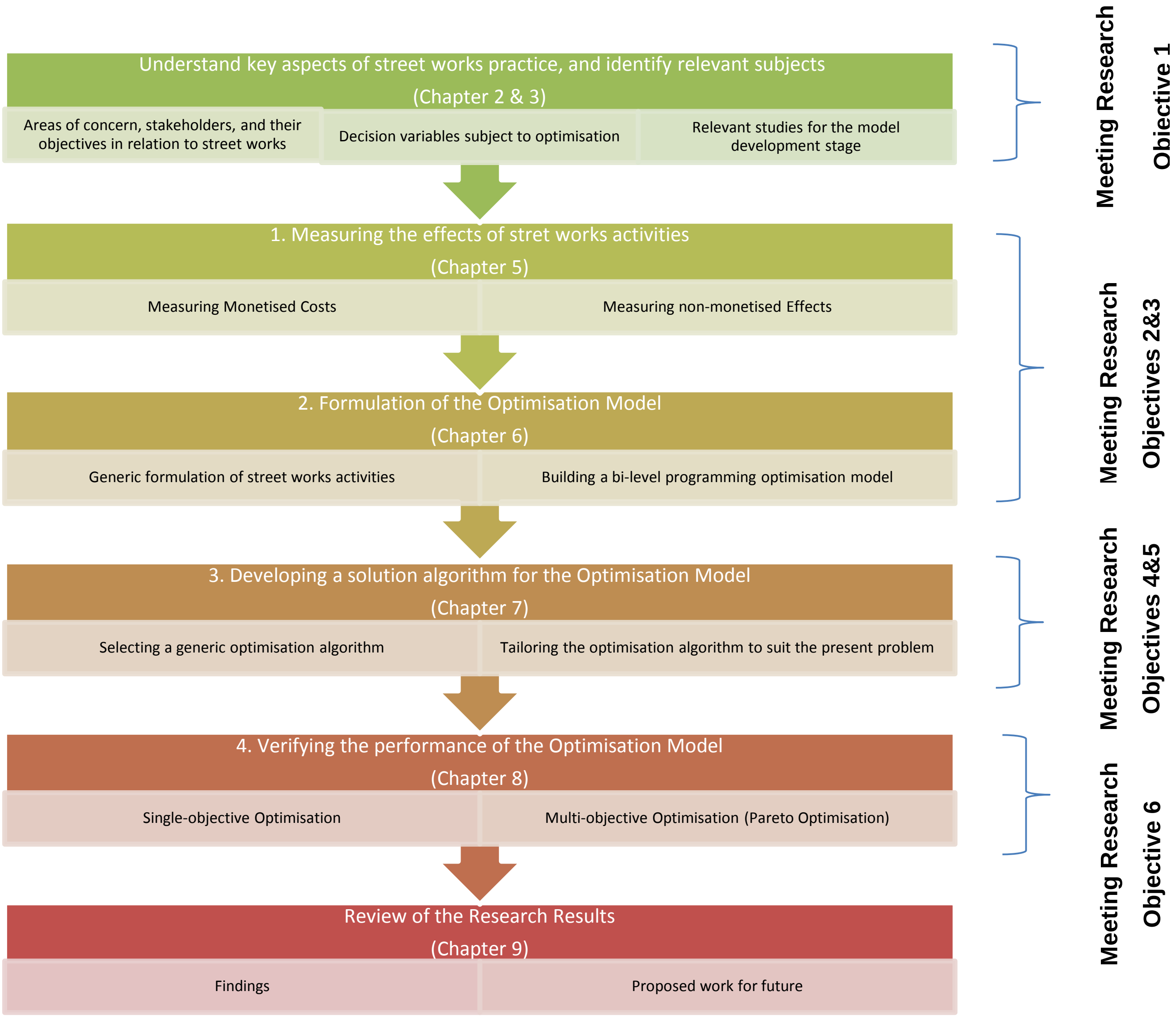


Figure 4-4 Thesis completion roadmap

4.2. Measuring the effects of street works activities

The optimum trade-off between the objectives of stakeholders can be achieved when the overall adverse effects of street works activities are minimised, and at the same time all of the constraints set for the implementation of the schemes are adhered to. The benefits resulting from street works activities in an optimisation model are regarded as *negative costs.* An optimisation model capable of finding such trade-offs will include one or a set of objective functions to measure the effects of street works schemes.

Chapter 5 describes the process of selecting two objective functions for the optimisation model of this study: These objectives correspond to the *monetised* and *non-monetised* effects of street works. While the methods used to measure the monetised effects are found to be well established in the existing literature, no suitable methodologies were found which could be utilised to measure the non-monetised effects of street works schemes in an urban traffic network.

The two objective functions of the optimisation model which are developed in chapter 5 are:

Primary objective function measures the monetised costs incurred by undertaking street works schemes in a network.

Following the review conducted in chapter 2 and 5, the primary objective function is defined as the summation of the six items which are shown in the following equation. These costs and their calculation methods – where presented - have been identified from the literature which are generally concerned with the cost-benefit analysis of highways mainteance and construction schemes, such as Yang (2010), Kandli et al. (2010), Tang et al. (2010) and particularly WebTAG 3.5.6 (Department for Transport, 2012d).

$$C_T^{\mathrm{A}} = C_D + C_W + C_C + C_I + C_A + C_M \qquad \text{(Eq 4.1)}$$

$\boldsymbol{C_T^{\mathrm{A}}}$ is the total monetised costs of street works schemes during the planning period *T*

$\mathbf{C_D}$ is total delay costs to road users, and is calculated based on attributing a fixed cost for each hour of delay per vehicle.

$\mathbf{C_W}$ is the cost of utility works. This item also includes the cost of necessary traffic management arrangements, and is normally calculated per each shift of works. It can include a fixed ‘set-up cost’ too.

$\boldsymbol{C_C}$ is the expenses resulting from variation in the completion date of the schemes: This is to account for the loss of benefits and/or incurred fines due to late completion of the works. Depending on the nature of a scheme, this item can be calculated based on the completion time of the works on a single link, or the completion of the scheme on the entire relevant links.

$\boldsymbol{C_I}$ is the idling costs during the implementation of a scheme. For instance for highway maintenance and construction schemes (e.g. Yang, 2010) the idling cost arise from the overhead expenses of the crew (labour and equipment) during non-active periods. An idling period normally takes place to avoid causing delays to road travellers during peak hours of the day, or peak days of the week, and is usually calculated as a fixed cost per one hour or shift of idled crew. Often a maximum allowable idling period is specified for a scheme.

$\boldsymbol{C_A}$ is the costs resulting from the increase in accident rates due to road capacity degradation. It is calculated based on taking an average cost for each accident, and assuming a fixed number of accidents per certain amount of vehicle hour of delays.

$\boldsymbol{C_M}$ is the additional operational and maintenance costs for road travellers due to implementation of street works schemes. It is calculated by a formula provided in WebTAG 3.5.6 (Department for Transport, 2012d).

The secondary objective function is associated with the disruptive effects of street works schemes which are expressed in qualitative terms.

Several examples of circumstances which can give rise to such disruptive effects of street works include: unsatisfied origin-destination travels resulting from closure of certain links at the same time, degraded capacity of certain links at some sensitive times (e.g. during or near the time of *special events*), and disruption to public services using certain links of the network. These effects are usually not considered or measured properly in the vast majority of transport network studies which entail evaluating road maintenance schemes, or other disruptive infrastructure projects.

In chapter 5 it is justified that a *fuzzy interface system*, associated with the fuzzy logic theory, can best suit the secondary objective function. This is mainly due to the subjective nature of the input variables of this objective function, including ‘time sensitivity’ of the disruption effects, and ‘accessibility degradation’ due to traffic management restrictions, and the nonlinear accumulative impacts of these variables. The review conducted in chapter 5 has revealed widespread and successful application of fuzzy logic theory in a broad range of transportation related studies due to having certain advantages over conventional mathematical methods. It will be shown in chapter 5 that a fuzzy inference system can provide maximum flexibility for network planners as to how they measure the perceived disruptive impacts of street works, based on different policies that they may adopt on road occupancy restrictions due to street works activities.

The fuzzy inference system developed in chapter 5, comprises two fuzzy sub-systems, each consisting of a number of fuzzy variables (embedding fuzzy membership functions) and several fuzzy rules in order to deduce a disruption index for every link, and origin destination of the network:

The following fuzzy variables have been selected as inputs of the fuzzy inference systems (the fuzzy attributes for each variable have been specified in parentheses):

- $\widetilde{x_1}$ Time sensitivity (high, low)
- $\widetilde{x_2}$ Connectivity degradation of a pair of origin-destination (highly degraded, slightly degraded)
- $\widetilde{x_3}$ Degradation of the accessibility of a given link (highly degraded, slightly degraded)

The disruption indices are also fuzzy variables as follows:

- $\boldsymbol{\widetilde{y_1}}$ Origin-destination related disruption (high, average, low)
- $\boldsymbol{\widetilde{y_2}}$ Link accessibility related disruption (high, average, low)

An example of the set of fuzzy rules to work out the above disruption indices for every origin-destination and link of the network is provided below:

- If $\widetilde{x_2}$ is slightly degraded, $\widetilde{y_1}$ is low
- If $\widetilde{x_2}$ is modestly degraded and $\widetilde{x_1}$ is moderate, $\widetilde{y_1}$ is average
- If $\widetilde{x_2}$ is highly degraded and $\widetilde{x_1}$ is high, $\widetilde{y_1}$ is high

- If $\widetilde{x_3}$ is slightly degraded, $\widetilde{y_2}$ is low
- If $\widetilde{x_3}$ is modestly degraded and $\widetilde{x_1}$ is moderate, $\widetilde{y_2}$ is average
- If $\widetilde{x_3}$ is highly degraded and $\widetilde{x_1}$ is high, $\widetilde{y_2}$ is high

The total Disruption Index of the network (consisting of *N* origin-destination movements and *M* links) for a planning period, representing the secondary objective function of the optimisation model, can be deduced as follows:

$$\widetilde{DI}_T = A \times \sum_{i=1}^{i=N} \sum_{t=1}^{t=T} k_i \times \tilde{f}\,(\tilde{x}_1\,,\,\tilde{x}_2) + B \times \sum_{i=1}^{i=M} \sum_{t=1}^{t=T} l_{i\times} \tilde{g}\,(\tilde{x}_1\,,\,\tilde{x}_3) \qquad \text{(Eq 4.2)}$$

Where:

$\widetilde{DI}_T$ is the total disruption index for the entire network during the planning period T (e.g. a calendar year)

A & B are the coefficients used to account for the relative importance of each type of disruption.

$\tilde{f}\ (\tilde{x}_1\ ,\ \tilde{x}_2)$ and $\widetilde{g}\ (\tilde{x}_1\ ,\ \tilde{x}_3)$, measured in a 0 to 100 scale, are respectively the fuzzy inference systems relating to disruption due to *origin-destination disconnection* and *link accessibility degradation.* They are calculated for every origin-destination movement and every link of the network by inferring *crisp* output values for $\tilde{f}$ and $\tilde{g}$ from the fuzzy input values of the inference systems.

To account for the relative importance of some origin-destination movements and links over the others, the coefficients k_i and l_i are applied to the $\tilde{f}\ (\tilde{x}_1\ ,\ \tilde{x}_2)$ and $\widetilde{g}\ (\tilde{x}_1\ ,\ \tilde{x}_3)$ in the above equation. These coefficient respectively represent the relative importance of each origin-destination and link of the network.

4.3. Development of the optimisation model

Once the objective functions of the optimisation model are established, chapter 6 describes the formulation of the optimisation model. This includes expressing the optimisation problem in mathematical terms, and explaining other major elements of the optimisation model and the way they interact with each other. This particularly includes the formulation of street works schemes within the optimisation model as it has a significant impact on the way the genetic algorithm solution model is developed in chapter 7.

4.3.1. Formulation of the optimisation problem in mathematical terms

The objective functions of the optimisation model were established as minimising the overall costs incurred by stakeholders due to undertaking the street works schemes (objective 1) together with the disruption index of the network (objective 2) during a planning period. These objective functions are sought to be minimised in the following way:

On the higher level, the problem involves deciding (by the network planner) on how to change the network configuration in such a way that the above objectives are minimised.

Subsequently in the next level of the problem road travellers will adapt their route choices based on the new network circumstances. The resulting delays to the affected road users can be deduced by using an appropriate traffic assignment model (as reviewed in section 3.1) on the degraded network. However, this in itself can entail solving another optimisation problem to obtain the results of the traffic assignment model of the degraded network. Furthermore with some type of complex schemes, an optimisation model may need to be developed and solved to deduce, for instance, the optimum allocation of resources required for undertaking the schemes (see the introduction of project scheduling optimisation models in section 6.7).

The phenomenon described above is an attribution of *bi-level programming* class of mathematical optimisation problems, which have been extensively studied in the context of transportation related studies. For instance *network design problems* which were reviewed in chapter 3 are generally a well-known class of bi-level programming problems.

Figure 4-5 shows the interaction between the higher and lower levels of the optimisation problem of this study, and the underlying variables associated with each level. The higher level optimisation variables which are of primary interest to the planner should be obtained by running the main optimisation algorithm of the model (described in chapter 7). The lower level optimisation variables are deduced by running other relevant optimisation algorithms inside the optimisation model.

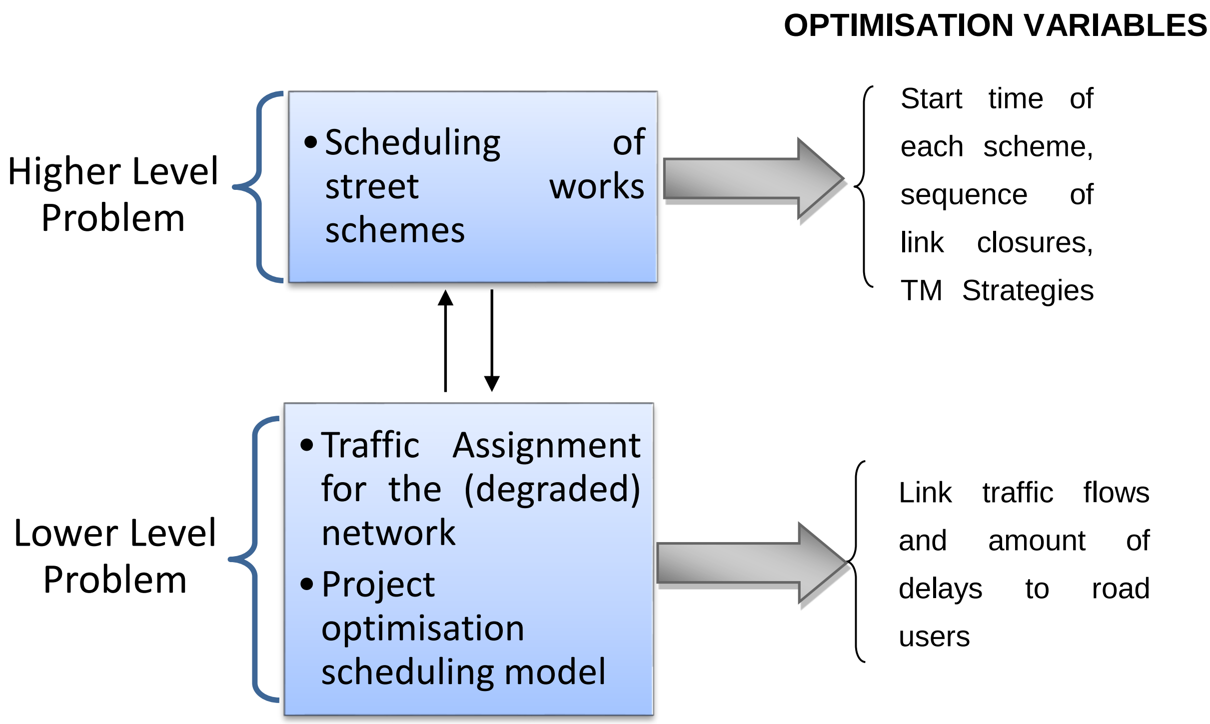


Figure 4-5 Illustration of the interaction between the higher and lower levels of the optimisation problem (reproduction of Figure 6-1)

The general formulation of a bi-level optimisation problem – with a single objective - for a transportation network is as follows (e.g. Yin, 2000):

$\min_{u} F(u, v(u))$ (Eq 4.3)

Subject to

$\mathrm{G}(\mathrm{u}, \mathrm{v}(\mathrm{u})) \leq 0$

Where $v(u)$ is implicitly defined by

$\min_{v} f(u, v)$

For a bi-objective optimisation problem, two objective functions are sought to be minimised at the same time, i.e. $\min_{u} F_1(u, v(u))$ & $\min_{u} F_2(u, v(u))$

The meaning of the above symbols, together with their description in the context of this study, are provided in Table 4-1.

Table 4-1 List of parameters associated with a general bi-level optimisation problem (reproduction of Table 6-1)

Symbol	**Description in a generic bi-level context**	**Description in the context of this study**
F_1& F_2	Objective functions of the upper-level decision maker (system manager)	The total costs and disruptions resulting from the completion of the street works schemes within a planning period
u	Decision vector of the upper-level decision maker (system manager)	Decision variables related to undertaking street works schemes (start times of the schemes, sequence of link closures, type of traffic management arrangements, etc.)
G	Constraint set of the upper-level decision vector	Constraints relating to the scheduling of the street works schemes planned in the network (e.g. earliest start times allowed for the schemes, latest allowable completion dates)
f	Objective function of the lower-level decision makers (i.e. travellers)	Travellers' objectives: seeking to minimise their own travel times, or travel costs under degraded network conditions (associated with Wardrop's

Symbol	Description in a generic bi-level context	Description in the context of this study
		User Equilibrium; alternative assumptions may be selected).
v	Decision vector of the lower level decision maker (travellers)	Traffic flows on the degraded network during the implementation of street works schemes
g	Constraint set of the lower-level decision vector	Constraints relating to the traffic assignment function and project optimisation scheduling model
H	The traffic network subject to configuration alterations	The traffic network subject to capacity alterations due to street works activities

4.3.2. Formulation of street works schemes

It is recalled from chapter 1 that the term *street works* in this study is defined in a very broad context to cover all planned activities which, once implemented, can reduce the capacity of the links of a traffic network. The duration and completion costs of street works schemes are two important parameters which should be calculated by the optimisation model of this study during the evaluation of different scenarios. Similar to other projects, the duration and costs of street works schemes are dependent on the *resources* allocated to them, including the level of labour and equipment, and the amount of working space available for the works.

In chapter 6, a general project scheduling formulation is identified in order to deduce the relationship between the available resources to a street works scheme, duration of the scheme, and the total cost of the scheme. This is referred to as 'the formulation of street works schemes' in this thesis.

The formula of a general scheduling problem, first introduced by Hindelang and Muth (1979), is provided by Wuliang and Chengen (2009) as minimising the following objective function:

$$F_c = \sum_{i \in V} \sum_{m \in M_i} \left(x_{im} . y_i . \sum_{k \in K_{im}} (ed_{im} . c_k) \right) + \sum_{i \in V} (u_k . f_n) \qquad \text{(Eq 4.4)}$$

The variables used in the above formula are defined in Table 4-2.

For the optimisation problem of this study and without undermining its generality, the entire works related to a single scheme on a link is regarded as one single activity within the project scheduling formulation. This approach is quite suitable for street works schemes conducted in urban environments where normally a single working area is available at a time on a link.

The link capacity available to the utility companies (e.g. either the whole area of a given link or half of the capacity of that link) is represented by an integer number *m* which is a *resource mode* – or in short just *mode* - by which a street works scheme is undertaken. An additional mode, accepting integer numbers, will be used to represent the traffic management strategies selected for the links. When appropriate, the number of these modes may be expanded to account for other options such as undertaking schemes during the day or overnight, number of working hours for a shift, and even the number of working areas on a link (e.g. multiple work zones).

When the values of the above modes are limited to only a few options, which is normally the case with most street works schemes in urban environments, it would be sensible to combine these modes to deduce a single *combined mode*. Consequently the cost and duration of a street works scheme for each link of the network can simply be deduced and passed to the optimisation model as a function of the value of this combined mode. The experimental tests provided in chapter 8 will use a combined resource mode variable with two feasible values to undertake a scheme for each link of the network.

Description of the other elements of the optimisation model is provided in chapter 6.

Table 4-2 List of variables in the general objective function of the project scheduling problem (reproduction of Table 6-2)

F_c	total cost of the scheme (project)
V	Project activities
M_i	Activity modes for the project activity *i*
k	a *renewable*[1] resource
d_{im}	Duration of an activity *i* when activity *i* is performed in mode *m*
ed_{im}	crashing duration when activity *i* uses resource k in the *crashing way*[2]
f_n	the finish time of the end activity
c_k	direct cost per unit time of k when k is used in crashing way
x_{im}	decision variable, equals 1 if activity *i* is performed in mode m and 0 otherwise
y_i	decision variable, equals 1 if activity *i* is performed in crashing way and 0 otherwise
u_k	cost per unit time of k
m	resource mode

Table notes:

1. Project resources are usually categorised as *renewable* (e.g. manpower resources) and *non-renewable* (e.g. machinery).

2. An activity can be executed in *crashing way* whereby its duration is shortened by spending project direct costs.

4.4. Solving the street works optimisation problem

Following the formulation of the optimisation problem which is described in chapter 6, a new chapter is needed in order to explain the development of a solution algorithm for the optimisation problem of this study. Chapter 7 therefore discusses: first, the selection of a suitable type of optimisation methodology; and second, the adaption of this optimisation methodology to suit the problem studied in this thesis. These main topics are preceded by an introductory discussion which aims to establish the need for using an optimisation algorithm, rather than adopting an alternative approach such as using an exhaustive search algorithm.

4.4.1. Selection of an appropriate type of optimisation algorithm

Since bi-level mathematical programmes are *NP-hard* (see, for instance, Arora, 2009) and many of them are *non-convex* (Miandoabchi and Farahani, 2011), they are difficult to solve by standard optimisation models, such as *branch and bound* or *enumerative algorithms*, since they could only be applied to optimise these problems for small networks. In such cases *meta-heuristic* algorithms such as *genetic algorithms*, *simulated annealing*, *ant colony optimisation*, *differential equation*, *tabu search*, or a combination of them - referred to as *hybrid meta-heuristics* - have been utilised with success in many transport modelling studies (Luke, 2009).

Among the above methods, as discussed in Yin (2000), it appears that genetic algorithms have been applied to a wider variety of problem domains including engineering, sciences, and commerce. This is due to their simplicity, minimal problem restrictions, global perspective and implicit parallelism.

Genetic algorithms (referred to as *GAs* in the following list) are search and optimisation procedures motivated by the principles of natural selection (Goldberg, 1989), and are different from the majority of other optimisation and search procedures in the following ways:

- GAs work with a coding of the parameter set and not the parameters themselves.
- GAs search from a population of points, not a single point. The traditional point-to-point method is prone to locating false peaks in many-peaked search spaces. By contrast, GAs work from a rich database of points (a population of strings), simultaneously climbing many peaks in parallel: thus the probability of finding a false peak is reduced over methods that go point-to-point.
- GAs use payoff (objective function) information, not derivative or other auxiliary knowledge. This characteristic makes a GA a more canonical method than many search schemes.
- GAs use probabilistic transition rules, not deterministic rules. GAs use random choice as a tool to guide a search toward regions of the search space with likely improvement.

In a genetic algorithm a population of *strings* (also called *chromosomes* or *individuals*) which are encoded as candidate solutions are gradually evolved towards better solutions. Successful application of the genetic algorithm to solve an optimisation problem heavily depends on the coding of the candidate solutions in a robust way. Therefore a section of chapter 7 describes in detail the way candidate solutions are coded in the genetic algorithm solution methodology proposed in this thesis.

It is very common to use off-the-shelf optimisation packages to solve many types of optimisation and scheduling problems in transport studies. MATLAB (developed by the MathWorks Inc., 2014d) which has been selected for the coding of the entire optimisation problem of this study includes single-objective and multi-objective genetic algorithm optimisation functions. These functions have the advantage of providing several built-in and readily-available options for different elements of the genetic algorithm functions, such as population generation, and cross-over and mutation operators. It is however still possible, and sometimes necessary, to define customised functions for each of these elements in order to improve the performance of the optimisation algorithm, and/or tailoring the optimisation algorithm for specific problems.

4.4.2. Development of a bespoke optimisation algorithm based on the genetic algorithms methodology

The literature review in various chapters of this thesis has shown that often meta-heuristic optimisation methodologies will need to be tailored for a given optimisation problem in order to be executable, and capable of producing viable results. In chapter 7, the following key elements of the proposed optimisation algorithm are devised based upon the genetic algorithm methodology.

- Structure of the candidate solutions (i.e. coding of the chromosomes)
- Adapting the genetic algorithm function to handle discrete type variables
- Selection of the crossover and mutation operators
- Development of the fitness function of the optimisation algorithm

Once these elements are devised, the optimisation algorithm will be complete and ready for performance evaluation. This is undertaken in chapter 8 by conducting several tests to optimise the implementation of three street works schemes, using a small hypothetical traffic network. This is due to the fact that using a small hypothetical network allows the interaction between the optimisation variables and the objective functions of the model, and the prevailing trade-offs, to be clearly visible from the optimisation results. Such clarity is unlikely to be available when using larger networks, due to the complexities arising from the increase in the number of optimisation variables.

4.5. Chapter concluding remarks

In order to guide this study towards achieving its objectives, a roadmap was devised in this chapter. This roadmap comprises a number of *stages* which should be completed in various chapters of this thesis. The key themes of the work undertaken within these stages were reviewed in this chapter:

Initially a literature review was undertaken to understand the underlying aspects of street works practice, and also to identity relevant subjects which can contribute to the development of the optimisation model of this study.

This literature review was followed by measuring the effects of street works activities in order to establish the objective functions of the optimisation model: This resulted in the development of two objective functions which were tasked to measure the monetised and non-monetised effects of street works schemes.

Next, the entire optimisation problem formulation will be developed (in chapters 5 and 6) to establish the relationships between the key elements of the optimisation model, including the input variables, sub-functions, objective functions, etc. Overall, the optimisation problem of this study was shown to be a bi-level programming type of mathematical optimisation problem.

Finally a solution algorithm based on the genetic algorithms methodology will be proposed (in chapter 7) for solving the optimisation problem.

Chapter 5
Selection of Appropriate Objective Functions for the Optimisation Problem

This chapter deals with measuring the effects of street works schemes by the optimisation model of this study:

First, a primary objective function is developed in section 5.1 to measure the effects of street works which are best measured in monetary terms.

Second, a fuzzy inference system is developed in section 5.2 in order to measure those effects of street works which are best measured in qualitative terms. This is preceded by justifying the application of fuzzy theory in the optimisation model, and identifying appropriate fuzzy parameters (e.g. fuzzy variables and rules) for the fuzzy inference system associated with the secondary objective function.

5.1. Development of the primary objective function

5.1.1. Identifying different types of road users' costs

Different types of cost born by society in relation to undertaking street works schemes were identified in section 2.2. Among these costs, costs to highways users (including road travellers on urban streets) appears to be the most significant, and have been studied more extensively and in greater depth in the context of evaluating transport improvement schemes:

In the majority of optimisation models which are concerned with changing the configuration of transport networks, reducing total road users' travel times in a network is regarded as the main objective. Such changes can be in the form of providing additional links, increasing link capacities, permanent or temporary traffic management schemes, work zones set-ups on network links, and so on. This is particularly the case with highways construction and maintenance improvement schemes which are studied in the context of network design problem studies (refer to section 3.3), as well as work zone optimisation problems which are introduced in this section. However in the more recent literature, other performance measures have been observed for network design problem models. A few examples include maximising network reserve capacity (e.g. Sumalee et al., 2009), maximising consumer surplus (e.g. Shi et al., 2014), maximising a measure of user benefit from travel (e.g. Hearn and Yildirim, 2002) or an equity index in order to ensure that benefits or costs are distributed fairly across different groups of travellers (e.g. using the Theil measure of equity; see Connors et al., 2005).

In practice, however, the effects of most road activities impacting on transport networks should be evaluated against the criteria published by the central or local governments which have identified the standard types of road users' costs, and often the way these costs should be accumulated. As such, minimising the sum of different costs incurred due to undertaking highways and street works in transport networks continues to be the main approach in most transport studies concerned with appraising transport scheme improvements.

A significant example relates to the work zone optimisation models (e.g. Kandil et al., 2010 and Tang et al., 2010 in the US) which entail evaluating the effects of highway maintenance activities on road travellers (work zone optimisation models are further reviewed in section 6): The three types of costs considered in these models which are incurred by road users include:

- Cost of delays to road users calculated based on a fixed value of users' time (e.g. $15/vehicle-hour in the US: Tang et al., 2010)
- Costs resulting from the increase in accident rates due to road capacity degradation. For instance in the formerly mentioned studies, a fixed number of crashes is attributed to each 100 million of vehicle hours of delay (Tang et al., 2010). The total cost of accidents is then calculated based on taking an average cost for each accident (e.g. $40,000 for each crash, assuming 40 accidents per 100 million vehicle hour of delay: Tang et al., 2010)
- Costs associated with increased vehicles operational and maintenance costs due to reduced speed and more frequent stops during the maintenance activities. This is calculated as a fixed cost per each vehicle hour of delay (e.g. $0.91/vehicle-hour in the US: Tang et al., 2010)

Monetised value of time figures which are used in the UK to deduce delay costs are provided in a publication by Department for Transport, namely WebTAG 3.5.6 (Department for Transport, 2012d), as a fixed cost for each hour of saving for travel time or delay to road users. The Department notes that these figures have been deduced for economic appraisal of highway schemes and the values suitable for other applications such as road user charging and toll roads could be different; therefore further guidance is promised. Value of time figures specified in the aforementioned document depend mainly on the type of vehicles and purpose of journeys, and are presented in two separate tables for 'value of working time per person' and 'value of non-working time per person'. These values are subject to increase or decrease each year in line with GDP variations, population growth and household growth.

The working values of time differ substantially across different vehicle occupants (e.g. car driver, car passenger, walker, etc.). However it is appreciated that in certain circumstances a common value of time should be used for all travellers, equalling the average of all workers value (i.e. £28.68 per hour of *resource cost* in 2010, where resource costs are defined as costs that are net of indirect taxation which are related to the prices paid by Government for goods and services). Based on vehicle occupancy figures, in practice the market price value of time for an average vehicle is also provided. This equals £13.91 per hour in 2010 prices.

To the author's knowledge and experience, for almost all maintenance schemes - as opposed to some major road construction projects - no new traffic count data are obtained, mainly due to cost and time constraints, and thus a single value of time figure for an average vehicle is used for appraising delay costs to road users.

In the UK, the QUADRO programme sponsored by the Department for Transport is utilised for calculating costs of delays, as well as vehicle operation costs due to maintenance works:

- **Cost of delays:** A fixed cost for each hour of delay is used in the model: Bourne et al. (2008) explain that delays are assessed by calculation of the relevant lost time, and applying the value of time figures published by the Department for Transport. These figures have been reported as £11.28 per hour (in 2008 prices) for the average vehicle by WebTAG 3.5.6 (Department for Transport, 2012d). It is also highlighted that (Bourne et al., 2008) in order to fully account for the delays caused by a given set of works, one not only needs to consider delay to the vehicles passing through it, but also the delays caused to vehicles diverting around the site and the delay caused to other vehicles on the roads used for diversion by the increased volume of traffic.

  Vehicle operating costs: QUADRO programme uses some models provided in WebTAG 3.5.6 (Department for Transport, 2012d) which have been developed mainly based on empirical research, to calculate vehicle operating costs, consisting of costs of fuel (or electricity for electric vehicles), oil and tyres and an element of maintenance. In addition an allowance for purchase of new vehicles has been considered.

  Fuel consumption is estimated by the following formula:

  $L = \frac{a}{v} + b + c.v + d.v^2$ (Eq 5.1)

  Where:

  L = consumption, expressed in litres per kilometre;

  v = average speed in kilometres per hour; and

  a, b, c, d are parameters defined for each vehicle category (petrol car, diesel car, etc.) in Table 10 of WebTAG 3.5.6 (p.16 Department for Transport, 2012d).

  Non-fuel operating costs which include oil, tyres, maintenance, depreciation and vehicle capital saving (only for vehicles in working time) are calculated by the following formula:

  $C = a1 + b_1/V$ (Eq 5.2)

  Where:

  C = cost in pence per kilometre travelled

  V = average link speed in kilometres per hour

  a_1 is a parameter for distance related costs defined for each vehicle category

b_1 is a parameter for vehicle capital saving defined for each vehicle category (this parameter is only relevant to working vehicles)

a_1 and b_1 are parameters defined for each vehicle category (petrol car, diesel car, etc.) in table 15 of WebTAG 3.5.6 (p.25 Department for Transport, 2012d).

The Department for Transport (2012d) acknowledges that other types of costs or considerations may prevail which can be impossible or difficult to be converted to monetary terms, therefore advises that they should be taken into account outside the QUADRO programme.

5.1.2. Costs and benefits of street works schemes experienced by works undertakers and their clients

In addition to the costs discussed above in relation to road travellers, the cost of street works schemes incurred by undertakers, and the benefits or losses (e.g. due to late completion of the works) experienced by street works undertakers and their customers should be taken into consideration by the optimisation model. Calculation of such costs very much depends on the nature of the street works activities. For instance in work zone optimisation studies (e.g. Yang, 2010), the key cost items include cost of the crew, equipment, and traffic management costs. These costs are normally calculated through the given rates for a working shift, and then accumulated over the study period.

Sometimes non-active periods could take place during street works activities. As such the idling costs arising from the overhead cost of the crew (labour and equipment) during non-active periods should also be taken into consideration. An idling period normally takes place to avoid causing excessive degradation to link capacity during peak hours of the day, and is usually calculated as a fixed cost per one hour or shift of idled crew.

As will be explained in chapter 6 in detail, this study considers street works equivalent to other construction and maintenance **projects** which are scheduled by planners to work out their costs and other underlying parameters (e.g. duration of the works) in advance. Therefore the optimisation model adopts a *project scheduling formulation* (see section 6.7) in order to deduce the costs of street works schemes within the optimisation model.

5.1.3. Formulation of the primary objective function

Following the above review, the primary objective function is associated with minimising the sum of the following items: total costs to road users (C_D) (including delays, vehicle maintenance and accidents), cost of street works (C_W) which also includes cost of necessary traffic management arrangements, the costs resulting from variation in the completion date of the schemes (C_C) and, if applicable, the idling costs associated with the schemes undertakers(C_I). This is shown by the following equation:

$$\boldsymbol{C_T^{A}} = \boldsymbol{C_D} + \boldsymbol{C_W} + \boldsymbol{C_C} + \boldsymbol{C_I} + \boldsymbol{C_A} + \boldsymbol{C_M} \qquad \text{(Eq 5.3)}$$

Subject to: various constraints which can be set by the planners (e.g. traffic authorities)

$\boldsymbol{C_T^A}$ is the total monetised costs of street works schemes during the planning period T

$\boldsymbol{C_D}$ is calculated based on attributing a fixed cost for each hour of delay per vehicle and vehicle maintenance and accident costs as mentioned before

$\boldsymbol{C_W}$ is normally calculated per each shift of works and can include a fixed set up cost too. It also includes the cost of traffic management arrangements during the works.

$\boldsymbol{C_C}$ is associated with the benefits accrued by early completion of the schemes (for each link or for all of the affected links), or in other terms, the losses which are incurred as a result of the delay in the completion of the street works schemes.

$\boldsymbol{C_I}$ is the idling cost: In work zone optimisation studies (e.g. Yang (2010)), the idling cost is associated with the overhead cost of the crew (labour and equipment) during non-active periods. An idling period normally takes place to avoid causing (excessive) degradation to link capacity during peak hours of the day, and is usually calculated as a fixed cost per one hour or shift of idled crew. Often a maximum allowable idling period is specified for a street works scheme on each link.

$\boldsymbol{C_A}$ is the costs resulting from the increase in accident rates due to road capacity degradation. It is calculated based on taking an average cost for each accident, and assuming a fixed number of accidents per certain amount of vehicle hour of delays.

$\boldsymbol{C_M}$ is the additional operational and mainteance costs for road travellers due to implementation of street works schemes. It is calculated based on a formula provided in WebTAG 3.5.6 (Department for Transport, 2012d).

When applicable, an additional index for the above parameters would refer to the costs associated with a specific street works scheme (e.g. $C_{D,i}$ refers to total delay costs to road users as resutl of implementation of scheme *i*).

The above items are considered the most significant types of costs in the vast majority of street works activities which are common to be calculated in monetary terms. However other types of costs or considerations may prevail in some cases which will need to be taken into account by the primary objective function should they be quantifiable in monetary terms. However a significant effect of street works schemes associate with their disruptive effects which will be discussed in the following section.

5.2. Development of the secondary objective function using fuzzy logic theory

5.2.1. Background

The disruptive effects of street works schemes can have consequences beyond the monetised costs which were reviewed previously, and in practice they are not always the definitive factors for selection of the underlying decision variables of street works activities such as start time of schemes, type of traffic management, etc. The following are some of the circumstances where degradation of link and network capacities due to street works are considered to have such disruptive effects beyond monetised costs

- Complete disconnection of an origin-destination in the network which is also called an *unsatisfied demand* (Jenelius et al., 2006), or incurring excessive delays by the travellers between an origin and a destination (Oh et al., 2011)

- Degradation of accessibility and increase in the vulnerability of a transport network (as reviewed in chapter 3) due to the closure of some links of the network, and thus inconvenience, emerging risks and possibly financial expenses which would be incurred by the local residents and businesses. This particularly includes the inconvenience or risks emerging from complete closure of certain links which are of particular importance to public services (police, ambulances, etc.). The level of such inconvenience and risks may vary substantially at different times:

  It should be noted that for some type of links and street works schemes, it may still be possible to provide access to residents and emergency services during a full link closure arrangement , whereas with some other types of street works and links this may not be possible: In both circumstances the impact on traffic levels may be similar but the level of disruption - associated with increase in vulnerability of the network and degradation of accessibility - can vary significantly.

- Avoiding degradation of link capacity at certain *sensitive* times of the day or days of the year for reasons such as: coincidence or even proximity to *special events* (which will be defined later in this chapter) and peak business and shopping activity periods, and importance of maintaining the image of a network for social or political reasons.

These circumstances can all be associated with the phenomenon of *disruption* to links and origin-destination movements of a traffic network, which is always regarded as a primary concern by the stakeholders during the process of scheduling street works schemes (recall the review in chapter 2). Other network performance indicators found in the literature, e.g. accessibility and vulnerability indicators reviewed in chapter 3, in their own rights are **not** the main concern of planners during scheduling of temporary road restrictions which are required for undertaking street works schemes.

However they may well be the focus of planners for studying schemes which cause long term / permanent network configuration changes.

The extent of such disruption will depend on the collective effect of a myriad of parameters, most notably: time sensitivity, accessibility degradation level of links, connectivity degradation of origin destinations and the importance of the affected links and origin / destinations. However such effects and parameters are very commonly expressed in qualitative terms with linguistic language (e.g. *very serious, serious, moderate*, *negligible*, etc.), and can be subject to some level of uncertainty, imprecision and subjectivity. Furthermore the interaction between these parameters, which need to be understood and measured in order to deduce an overall disruption effect, can be quite complex too.

The issues mentioned above in relation to the underlying problem of this study are very common with many other transportation related studies. For instance in his review paper on the application of fuzzy systems, Teodorovic (1998) highlights the fact that a wide range of transportation engineering parameters are characterised by uncertainty, subjectivity, imprecision and ambiguity which are often the characteristics of linguistic information. A number of such examples include: *long* or *severe* delays, a *short* path and *wide* carriageway lanes. Furthermore the relationship between different parameters can be nonlinear and imprecise, and thus difficult or impossible to be formulated by ordinary mathematical expressions.

In order to address the above issues, modellers have chosen to use fuzzy models, associated with the utilisation of fuzzy sets and fuzzy logic inference systems (hereafter collectively referred to as ‘fuzzy logic theory’), in various traffic and transportation study fields. A comprehensive review of the applications of fuzzy theory in relation to more classic types of transportation-related studies has been provided by Teodorovic (1998): Table 5-1 includes some of the studies mentioned in the aforementioned reference together with several more recent examples.

Table 5-1 Examples for the application of fuzzy sets theory in transportation-related studies

Subject	**Examples**
Trip generation	(Wang and Mendel 1992)
trip distribution	Kalia and Teodorovic (2003)
modal split	Teodorovic and Kalic (1996)
route choice	Teodorovic and Kikuchi (1990)
traffic assignment	Akiyama et al. (1994); Ghataee and Hashemi (2009b)
transportation investment projects	Tzeng and Teng (1993)
traffic control at intersections	Pappis and Mamdani (1977)
Traffic control in corridors	Nakatsuyama et al. (1983)
Network control	Chiu (1992)
Accident analysis and prevention	Akiyama and Shao (1993)
highway capacity and level of service	Chakroborthy and Kikuchi (1990)
vehicle and crew routing, scheduling and dispatching problems	Larson and Odoni (1981)
Air transportation	Larkin (1985)
River transportation	Vukadinovic and Teodorovic (1994)
Network Design Problem	Ghataee and Hashemi (2009)
Evaluation of transportation service quality	Awasthi et al. (2011)
Construction project (including transportation infrastructure) risk management	Zeng et al. (2007)
Network Vulnerability Analysis	El Rashidy and Grant-Muller (2014)

Fuzzy set theory is largely attributed to Zadeh (1965) who introduced the concept of fuzzy sets whereby members of a given set can belong to that set with different levels of membership between 0 to 1. Appendix A contains some complementary information about fuzzy theory in relation to the development of the optimisation model of this thesis.

The following benefits have been specified in relation to using fuzzy theory in various modelling problems (MathWorks Inc, 2014a):

Fuzzy logic:

- is conceptually easy to understand
- is flexible
- is tolerant of imprecise data
- can model nonlinear functions of arbitrary complexity
- can be built on top of the experience of experts
- can be blended with conventional control techniques
- is based on natural language

When a problem consists of different rules to generate an output, fuzzy logic makes it easy to express those rules by common sense statements which are easy to be interpreted both by experts and also non-expert decision makers. It also makes it easy (as to be seen later) to combine the rules to obtain an overall output. This is particularly important when problems are computer coded to provide a neat and clear structure of the codes which are used to express the effects of different rules. Furthermore subsequent modifications to a fuzzy logic based model that is coded by a computer programming language are relatively easy. For instance a model can be recalibrated easily by simply shifting the fuzzy set that defines a *quality* (associated with a fuzzy variable) without rewriting the rules. Conversely for a non-fuzzy logic computer code such modifications can be quite difficult to handle, particularly with complex problems, as it entails a lot of changes to the structure of the relevant algorithms. Moreover it is often not apparent how the algorithm works to someone who did not see the original design process.

These advantages have been demonstrated in MALTAB Fuzzy logic toolbox user guide (MathWorks Inc., 2014a) for a simple problem of deducing the appropriate amount of tip paid to a waitperson in a restaurant based on the quality of food and quality of service, by using only three simple rules. The fuzzy logic approach clearly proved advantageous over the non-fuzzy approach (the latter is based on specifying many conditional statements in the problem algorithm). For complex problems with more variables and rules, the benefits of using fuzzy logic will be yet more significant.

As to be shown in the next section the secondary objective function of this study should embed several imprecise input variables which are best expressed by linguistic statements, together with several rules for these variables, in order to deduce a disruption index for a given traffic network subject to street works schemes. The input values and rules can be subject to change based on the policies and judgements of the relevant policy makers and stakeholders, as well as for reasons such as sensitivity analysis exercises. As such the benefits of fuzzy logic theory which were mentioned earlier are generally applicable to the underlying problem of this study too. Therefore fuzzy theory is adopted in this study for measuring disruption levels in the transport networks which are affected by street works schemes. This will be explained in the following section:

5.2.2. Identifying the fuzzy variables impacting on the level of disruption

The discussion provided in the previous section has led to identifying the following two factors which cause disruption to the users of a traffic network:

1. *connectivity degradation* of an origin-destination (factor 1), associated with full closure of a given origin-destination, or the experience of excessive delays by the travellers of that origin-destination

2. *accessibility degradation* due to restrictions caused by some types of traffic management arrangements on certain network links, affecting mainly local residents and public services in the network (this may be dubbed 'accessibility degradation of a link' in this chapter)

The level of disruptions perceived by the network users can vary based on a third factor, namely the t*ime sensitivity* of the disruptive events.

The above factors are measured by fuzzy variables using fuzzy attributes such as 'highly degraded', 'slightly degraded', and 'very sensitive'.

Any variables associated with the factors 1 and 2 above are assumed to be based on normal time circumstances, and their effects can then vary as a result of the variations in factor 3, i.e. time sensitivity of the disruptions. However an alternative approach can be envisaged whereby the fuzzy variables associated with factors 1 and 2 may accept varying values at different times. This approach however can unduly complicate the underlying inference system (as to be explained later in this section) by unnecessarily increasing the number of input variables of the system.

The two types of resulting disruption are highlighted below:

- The *origin-destination related disruption* is perceived by general network travellers which could be barred from reaching certain destinations due to link closures (DI_1).

- The *link-related disruption* is mainly related to the residents and public services which are concerned with the condition of specific links of the network (DI_1).

The level of disruption to a network at a given time corresponds to the joint effect of the above factors and is deduced by using *fuzzy rules* (see the following section). Disruption is also a quality which is explained by fuzzy variables and measured by fuzzy linguistic attributes such as 'high' and 'low'. These attributes belong to fuzzy sets which map crisp input values - i.e. numerical values from, for instance, a 0 to 10 scale- to a membership degree number between 0 to 1 using a fuzzy membership function (this will be further explained in section 5.2.3).

The overall disruption to the network at a particular time can be deduced by adding the above two types of disruption:

$DI_T = a \times DI_1 + b \times DI_2$ (Eq 5.4)

The coefficients a & b are used to account for the relative importance of each type of disruption which can be set by the relevant transport experts and policy makers.

The fuzzy inference systems which are used to deduce DI_1 and DI_2 are described in the following section. This includes explaining (in sections 5.3.2.1 to 5.3.2.3) how the fuzzy input variables introduced in this section should be represented through appropriate fuzzy membership functions.

5.2.3. Description of the process of deducing disruption values using a fuzzy inference system

Fuzzy inference is the process of formulating a mapping structure, using fuzzy logic rules, in order to deduce an output from the inputs of the inference system. The input values are expressed by numerical crisp values belonging to a scaling range, for instance 0 to 10. The membership functions of the fuzzy inference system will then be used to identify the degree of membership of an input value to the underlying fuzzy variables.

For instance in Figure 5-1, it can be observed that for Input 1 = 8 (input 1 is associated with the level of *accessibility degradation*), the degree of membership to the 'high' attribute is 0.7.

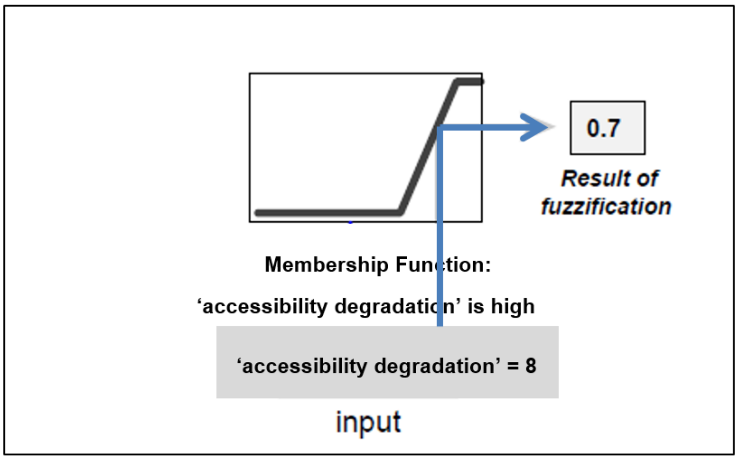


Figure 5-1 Deducing a membership degree value using a fuzzy membership function

Various membership functions have been proposed in the literature (Ross, 2005). In MATLAB fuzzy logic toolbox the shape of membership functions can be custom-built to suit a specific application, however a wide range of standard and well-known functions which suit many common applications are available. In appendix A some common types of membership functions are provided.

For the membership functions provided in this study in sections 5.2.3.1 to 5.2.3.2 and 8.2, triangular and trapezoid membership functions have been used. This is because these functions are by far the most common forms encountered in practice, and are relatively simply in terms of calculating membership grades (El-Rashidy and Grant-Muller, 2014; Torlak et al., 2011; Ross, 2005)

The fuzzy inference process adopted in this study is a Mamdani inference system which is known as the most widely used fuzzy inference system (MathWorks Inc., 2014a), and is supported by MATLAB Fuzzy Logic Toolbox Manual. It is based on the work mainly attributed to the late Professor Mamdani (e.g. Mamdani & Assilian, 1975) and involves taking the following five steps (MathWorks Inc., 2014a):

1. Fuzzification of the input variables

2. Application of the fuzzy operator in the antecedent (i.e. AND or OR, depending on the fuzzy *rules* of the model).

3. Application of the *implication* method (e.g. the MIN method)

4. Aggregation of the consequents across the *rules*

5. Defuzzification

The above steps have been briefly described in Appendix A. For an example in the context of this study, Figure 5-2 schematically illustrates these steps for deducing a 'disruption index' for the network using a fuzzy inference system comprising three fuzzy input variables and their associated fuzzy membership functions, together with the following three fuzzy rules, where fuzzy input variables are specified in italic letters (note that deducing a disruption index for traffic networks is explained in the following section of the thesis):

- If *link accessibility* is slightly degraded, then *disruption* is low
- If *link accessibility* is modestly degraded and *time sensitivity* is moderate, then *disruption* is average
- If *link accessibility* is highly degraded and *time sensitivity* is high, then *disruption* is high

The aforementioned steps for the fuzzy inference system shown on Figure 5-2 are:

1. First, the amount of membership degrees to the membership functions (diagrams 1 to 6) are deduced based on the input values for *link accessibility degradation* level, and *time sensitivity* level. The output is a set of crisp values associated with membership degrees (the resulting figures are not shown on Figure 5-2).

2. Second, the fuzzy operator AND is applied for each rule in order to generate a crisp output value for each rule (the resulting values are not shown on Figure 5-2).

3. Third, the output values of the previous steps are used to truncate the membership functions of the *disruption* variable (output: the truncated areas filled in blue on diagrams 7 to 9).

4. Fourth, the truncated areas of the last step are aggregated together (the result is shown on diagram 10 as the area filled in blue)

5. Last, the centroid of the blue area on diagram 10 is calculated as the output of this fuzzy inference system, representing the disruption index of the network (calculated as 46.7, in a 0 to 100 scale, on Figure 5-2).

It should be noted that different traffic network authorities can well have different understanding, priorities, tolerance and evaluation methods in relation to the perceived disruption due to network capacity degradation. The ‘fuzzy system’-based assessment method presented in this study guarantees maximum flexibility to address such issues. Hence with no need to change the general form of the fuzzy model presented here, different rules, weighting factors and membership functions can be used to account for such differences in policies and expert opinions. Indeed such flexibility could not have been provided by conventional algebraic equations.

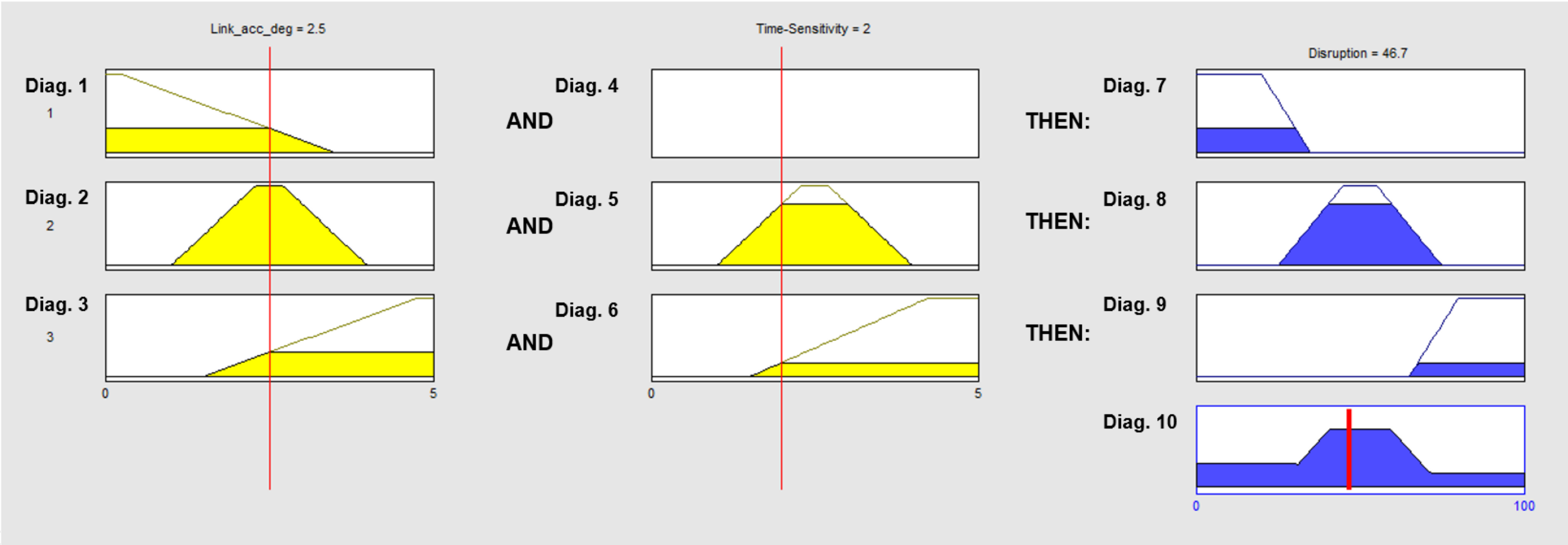


Figure 5-2 An example of the application of Mamdani fuzzy inference system to deduce disruption level

5.2.3.1. Representation of origin-destination connectivity degradation

Total disconnection between an origin and destination of a traffic network is one of the disruptive circumstances which cannot be evaluated by traditional assessment methods which measure the monetised costs incurred by road users (Jenelius et al., 2006). Apart from total disconnection, even excessive increase in travel time between an origin destination, due to a given scenario of street works activities, is considered to be very undesirable in a network due to equality concerns, even if that scenario causes less overall delay to the network compared to other available options. This issue is noticed in an optimisation model, developed by Oh et al. (2011), for coordination of multiple highway construction and maintenance projects: To address this they set a second performance measure, represented by a secondary objective function alongside the primary one, to evaluate the average increase of travel time between origins and destinations due to construction and maintenance projects (the primary objective function of the model measures the total construction and delay costs).

An origin-destination disconnection occurs when all routes between a given origin and destination are closed. With elastic traffic assignment conditions introduced in section 3.1, this situation can virtually happen when the minimum cost of travelling between an origin-destination increases to such a high level that no one would be prepared to travel between this pair due to the excessive travel costs.

Figure 5-3 shows the proposed format of a function which relates the c_i coefficient, as defined below, to the level of connectivity degradation between a given origin-destination (it is assumed that the numerator is always larger than the denominator)

$$c_i = \frac{Minimum\ OD\ travel\ cost\ under\ degraded\ conditions}{Minimum\ OD\ travel\ cost\ under\ un{-}degraded\ conditions} \qquad \text{(Eq 5.5)}$$

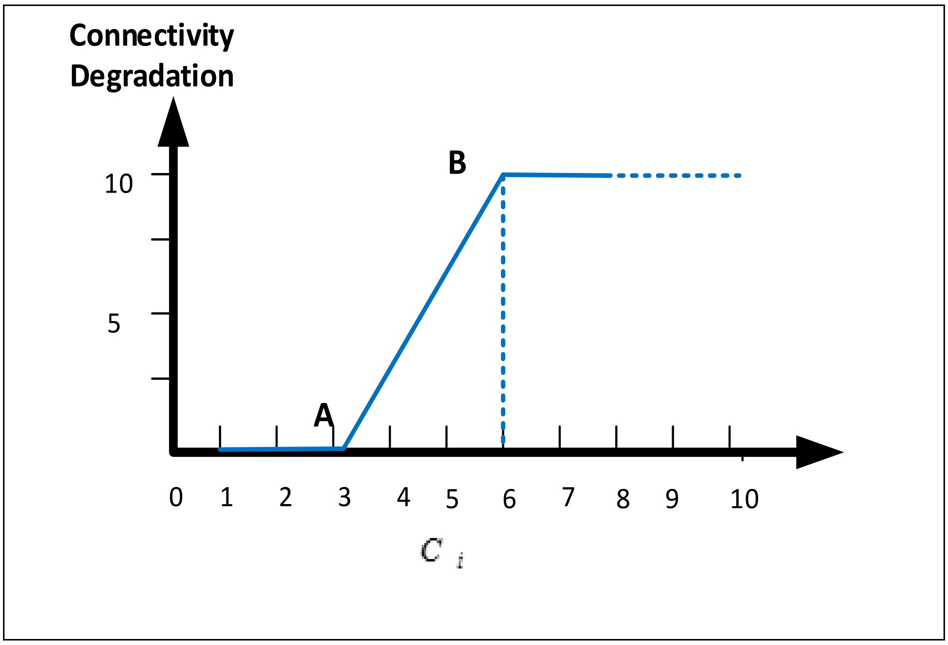


Figure 5-3 Example of a connectivity degradation function of an origin-destination

The given origin-destination is considered un-degraded (score = 0) up to the point where C_i reaches point A; it then starts to increase linearly until point B beyond which the connectivity of the given origin-destination is considered to be completely diminished (score = 10). This format is suitable for both static and elastic traffic demand conditions, assuming $C_i = \infty$ for those origin destinations which have been completely blocked.

Disruption to an origin destination is measured by membership degrees to ‘high’ and ‘low’ attributes using the proposed format of the following membership functions:

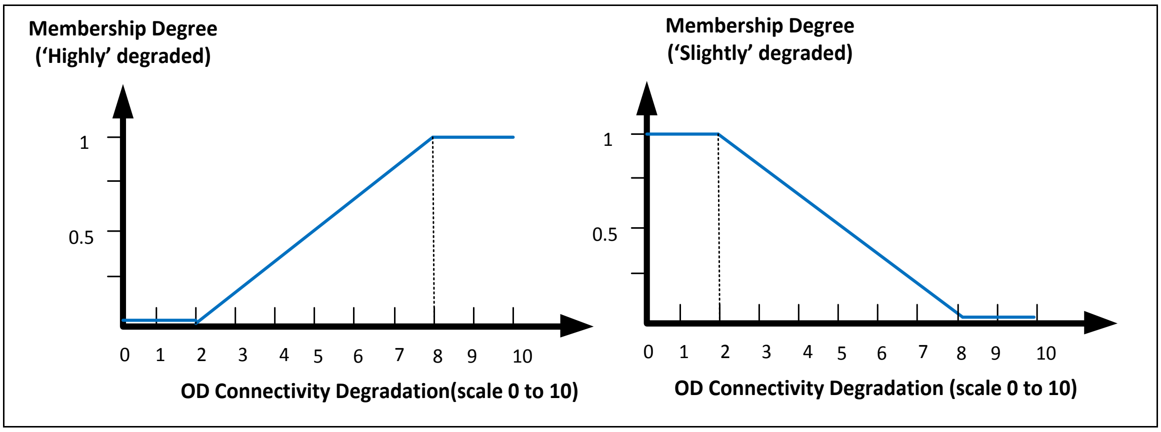


Figure 5-4 Examples of fuzzy membership functions for origin-destination ‘connectivity degradation’

The above representation ensures that not only the disruption due to total origin-destination closures would be treated as very disruptive, but also are the scenarios causing excessive delays to one or several origin-destinations.

5.2.3.2. Representation of accessibility degradation due to traffic management restrictions

During street works activities, accessibility of different links can be reduced at varying levels, mainly depending on the characteristics (e.g. number of lanes and width) of the affected links, and the type of traffic managements selected for them. While some of the accessibility measures and vulnerability indicators which were mentioned in section 3.2 may help with quantifying accessibility degradation levels, this study argues that using a scaling system and scores devised by the traffic planners and experts is likely to be the best approach. This is due to the subjective nature of the factors and circumstances which impact on the accessibility degradation perceived by the stakeholders:

Table 5-2 , for instance, specifies the level of accessibility degradation for a given link in a 0 to 10 scale for a number of traffic management strategies.

Table 5-2 Examples for degradation of accessibility due to various traffic management strategies

Traffic Management Strategy	Accessibility Degradation (0 to 10 scale)
Partial (one lane) closure of the link (access for residents and businesses is maintained)	1
Partial closure of the link, involving closure of the relevant roadside businesses	3
Full closure of the link, only allowing access to residents and public services	8
Full closure of the link, with no access to residents and public services	10

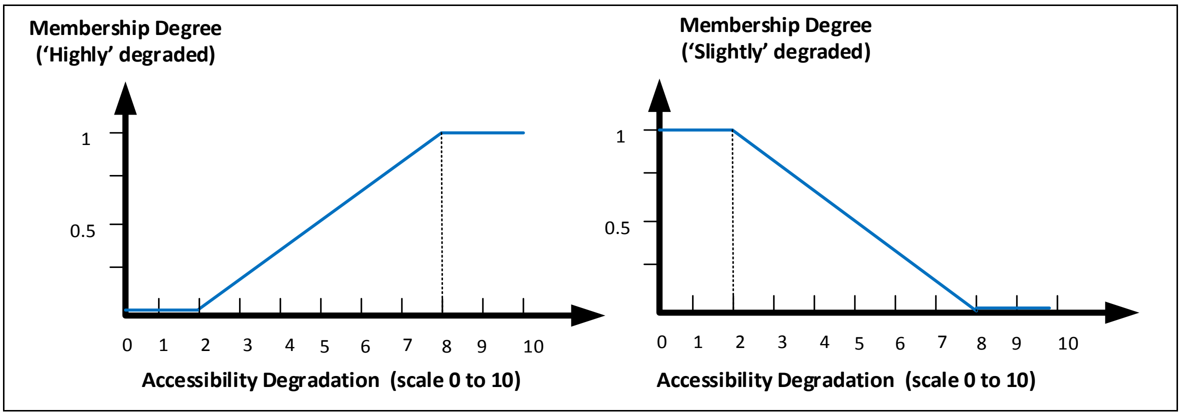


Figure 5-5 Examples of fuzzy membership functions for 'accessibility degradation' using the numerical values provided in Table 5 2.

5.2.3.3. Representation of the time sensitivity of disruptive events

The sensitivity of the timing of disruptive events, including street works activities, is a major factor in determining the perceived level of disruption by the stakeholders. Such sensitivity can sometimes be independent of the volume of traffic using the network at specific times. The most significant case envisaged for this relates to the proximity or coincidence of street works activities to special events (as defined below). This is normally deemed a major disruption to the community and the users of a traffic network, and is to be avoided as much as possible.

A definition for a special event is provided by the (American) National Highway Institute (quoted in a report by Transportation Research Board, 2003) as “an occurrence that abnormally increases traffic demand”. Therefore they are different to road incidents or construction & maintenance activities that typically restrict the roadway capacity. Under this definition, special events may include sporting events, parades, fairs and other planned events. However some circumstances can certainly be envisaged where a special event does not increase traffic demand, for instance through posing restrictions on normal travellers. Some special events, such as a marathon run, also involves complete blockage or significant traffic-reduction measures for parts of a traffic network.

To suit the scope of this thesis, the term *special event* in this study is defined more broadly to cover any conditions where the perceived disruption due to a planned degradation of network capacity would be regarded as much more serious than if the degradation were to occur in normal circumstances.

Figure 5-6 shows the proposed format of the functions which explain how time sensitivity varies in a 0 to 10 scale during a planning period due to two special events.

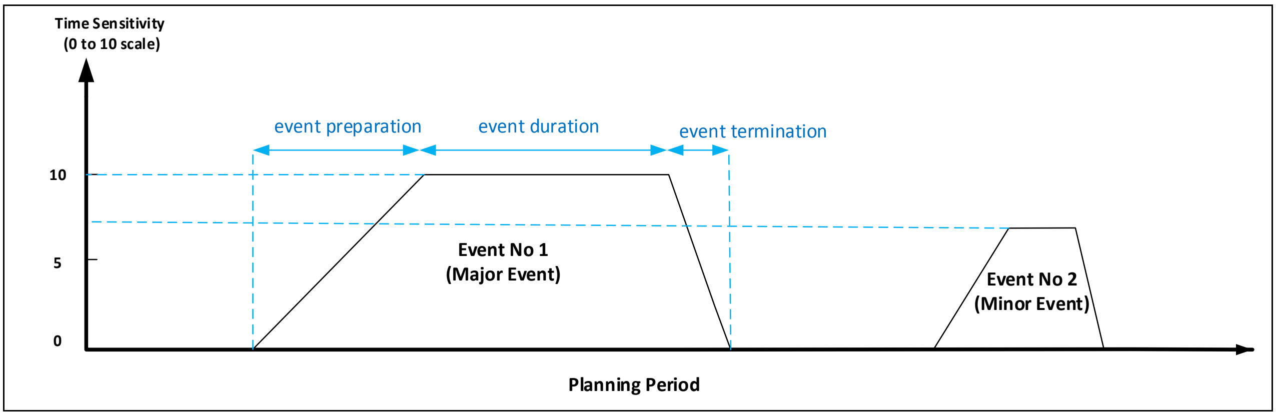


Figure 5-6 Example of representation of time sensitivity during special events

Figure **5-7** shows two example of membership functions associated with ‘high’ and ‘low’ attributes which are meant to deduce membership degrees (on the vertical axis) of different time sensitivity values (on the horizontal axis).

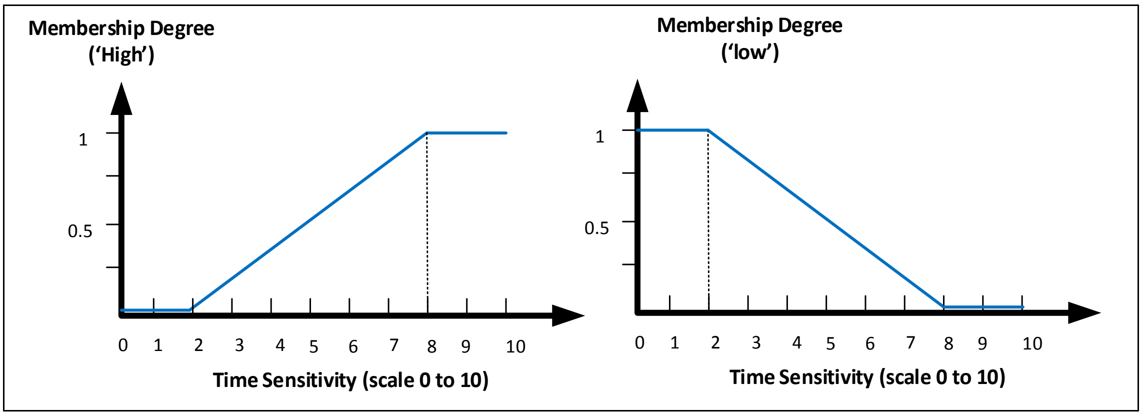


Figure 5-7 Examples of fuzzy membership functions for 'time sensitivity'

5.2.4. Mathematical expression of the secondary objective function

It was highlighted earlier in this chapter that the secondary objective function of the optimisation model intends to measure the disruptive effects resulting from street works activities. These effects are beyond those which are measured in monetary terms in section 5.1 by the primary objective function. It was argued that disruption and the underlying factors causing it are most suitable to be expressed in qualitative terms. beyond the monetised costs that reviewed previously; they have been deemed more appropriate to be expressed qualitatively by a second objective function. As such two fuzzy interface systems, mainly consisting of several fuzzy variables, their membership functions and the fuzzy rules, were developed in this chapter to measure the disruptive effects of street works on origin-destination movements as well as degradation of link-related accessibility.

The following fuzzy variables are the inputs to the fuzzy inference systems (the fuzzy attributes corresponding to each variable have been specified in parentheses):

- $\widetilde{x_1}$ Time sensitivity (high, moderate, low)
- $\widetilde{x_2}$ Connectivity degradation of a pair of origin-destination (highly degraded, modestly degraded, slightly degraded)
- $\widetilde{x_3}$ Accessibility degradation of a given link (highly degraded, modestly degraded, slightly degraded)

The two resulting disruption indices (i.e. the outputs of the , before defuzzification, are also fuzzy variables as follows:

- $\widetilde{y_1}$ Origin-destination related disruption (high, average, low)
- $\widetilde{y_2}$ Link accessibility related disruption (high, average, low)

The following fuzzy rules are applied in order to work out the above disruption indices for every origin-destination and every link in the network.

For origin-destination related disruption:

- If $\widetilde{x_2}$ is slightly degraded (and irrespective of the $\widetilde{x_1}$ value), $\widetilde{y_1}$ is low
- If $\widetilde{x_2}$ is modestly degraded and $\widetilde{x_1}$ is moderate, $\widetilde{y_1}$ is average
- If $\widetilde{x_2}$ is highly degraded and $\widetilde{x_1}$ is high, $\widetilde{y_1}$ is high

Similarly for link accessibility related disruption:

- If $\widetilde{x_3}$ is slightly degraded (and irrespective of the $\widetilde{x_1}$ value), $\widetilde{y_2}$ is low
- If $\widetilde{x_3}$ is modestly degraded and $\widetilde{x_1}$ is moderate, $\widetilde{y_2}$ is average
- If $\widetilde{x_3}$ is highly degraded and $\widetilde{x_1}$ is high, $\widetilde{y_2}$ is high

The total *Disruption Index* of the network (consisting of *N* origin-destination movements and *M* links) for a planning period, associated with the secondary objective function of the optimisation model, can be deduced as follows:

$$\widetilde{\boldsymbol{DI}}_{\boldsymbol{T}} = \boldsymbol{A} \times \sum_{i=1}^{i=N} \sum_{t=1}^{t=T} \boldsymbol{k_i} \times \tilde{\boldsymbol{f}}\,(\tilde{\boldsymbol{x}}_1\,,\, \tilde{\boldsymbol{x}}_2) + \boldsymbol{B} \times \sum_{i=1}^{i=M} \sum_{t=1}^{t=T} \boldsymbol{l_i} \times \tilde{\boldsymbol{g}}\,(\tilde{\boldsymbol{x}}_1\,,\, \tilde{\boldsymbol{x}}_3) \qquad \text{(Eq 5.6)}$$

Where:

$\widetilde{DI}_T$ is the total disruption index for the entire network during the planning period T (e.g. a calendar year)

A & B are the coefficients used to account for the relative importance of each type of disruption.

$\tilde{f}\,(\tilde{x}_1\,,\, \tilde{x}_2)$ and $\tilde{g}\,(\tilde{x}_1\,,\, \tilde{x}_3)$ are the fuzzy inference systems relating to disruption due to *origin-destination disconnection* and *link accessibility degradation.* They are calculated, respectively, for every origin-destination movement and every link of the network by inferring crisp output values – belonging to the 0 to 100 range - from the input values of the inference systems.

To account for the relative importance of some origin-destination movements and links over the others (if deemed appropriate by the planners) the coefficients k_i and l_i are applied to the $\tilde{f}\,(\tilde{x}_1\,,\, \tilde{x}_2)$ and $\tilde{g}\,(\tilde{x}_1\,,\, \tilde{x}_3)$ in the above equation. k_i and l_i represent the relative importance of each origin-destination and link of the network.

5.3. Chapter concluding remarks

The present chapter was dedicated to measure the effect of street works schemes on the stakeholders, since these effects will need to be minimised by the optimisation model of this study in order to deduce optimum street works schemes options. To do so:

First, a primary objective function was formulated to measure those effects of street works which are available and commonly expressed in monetary terms. This mainly includes the cost of delays to road users, car maintenance costs, and cost of undertaking schemes to the undertakers (including penalties and loss of benefits due to delaying the schemes).

Second, the thesis identified the main effects of street works activities which are beyond those taken into account by the primary objective function and are collectively referred to as 'disruption'. The underlying factors causing such disruption were categorised into the connectivity degradation of the origin-destinations of a network, and accessibility degradation to the stakeholders. A third factor is the 'time sensitivity' of the disruptive effects which can significantly impact on the level of disruption perceived by the stakeholders.

It was noted that due to the nature of these factors and their relationships - characterised by uncertainty, subjectivity and impreciseness associated with qualitative attributes – it will be advantages to use fuzzy inference systems to deduce the relationship between the aforementioned factors and their resulting disruptive effects. Subsequently the fuzzy inference systems to measure two types of disruptive effects arising from street works activities were formulated in this chapter, and then embedded into a secondary objective function for the optimisation model.

Chapter 6
Formulation of the optimisation model

Following the work undertaken in the previous chapter to identify suitable objective functions for the optimisation problem of this study, this chapter intends to develop and describe the remaining elements of the optimisation model. The solution algorithm of the optimisation model will be developed in chapter 7.

As the first step, the general formulation of the optimisation problem in mathematical terms is presented in this chapter. Subsequently other underlying aspects of the optimisation model such as formulation of street works schemes, the interaction between the two levels of the optimisation problem, and the methodology used to deduce the amount of delays incurred by the affected road travellers are described in the following sections of this chapter.

The outcomes of this chapter aim to assist with developing an appropriate solution algorithm for the optimisation problem (discussed in chapter 7).

6.1. Formulation of the optimisation problem with mathematical expressions

A key component of the optimisation model is the objective functions which are subject to minimisation: They were established as minimising the overall costs incurred by the stakeholders due to undertaking a given number of street works schemes (objective 1), together with the total disruption imposed on the network (objective 2) during a planning period.

The problem studied in this study - at one level - involves deciding on how to change the configuration of a network, mainly through the type and duration of the associated traffic management schemes, so that the above objectives are minimised. Subsequently in a lower level of the problem, the road travellers will have to adapt their route choices based on the new network conditions. The resulting delays to the affected travellers can be deduced by applying an appropriate traffic assignment model to the degraded network. Usually this in itself entails solving another optimisation problem which is associated with solving the traffic assignment problem for the network. Furthermore with some type of complex schemes, an optimisation model may need to be developed and solved to deduce, for instance, the optimum allocation of resources which are required for undertaking the schemes. This will be discussed later in section 6.7.

The characteristics described above belongs to bi-level programming class of mathematical problems, and have been sufficiently studied in the context of transportation related studies. For instance network design problems which were reviewed in chapter 3 are generally a well-known class of bi-level programming problems.

Figure 6-1 shows the interaction between the higher and lower levels of the optimisation problem of this study, and the underlying variables associated with each level. The higher level optimisation variables which are of primary interest to the planner should be obtained by running the main optimisation algorithm of the model (described in chapter 7). The lower level optimisation variables are deduced by running other relevant optimisation algorithms inside the main optimisation model.

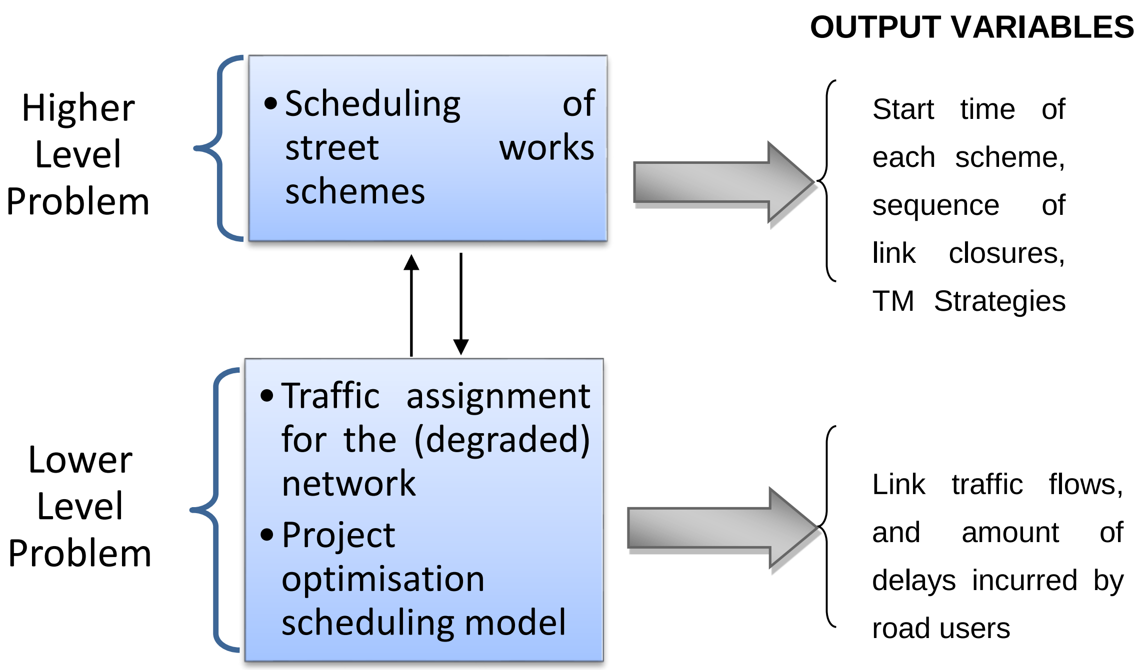


Figure 6-1 Illustration of the interaction between the higher and lower levels of the optimisation problem

The general formulation of a bi-level optimisation problem for a transportation network is as follows (e.g. Yin, 2000):

$\min_{u} F(u, v(u))$ (Eq 6.1)

Subject to

$\mathrm{G}(\mathrm{u}, \mathrm{v}(\mathrm{u})) \leq 0$

Where $v(u)$ is implicitly defined by

$\min_{v} f(u, v)$

For a bi-objective optimisation problem, two objective functions are sought to be minimised at the same time, i.e. $\min_u F_1(u, v(u))$ & $\min_u F_2(u, v(u))$

The meaning of the notations used in the above formula, together with their description in the context of this study, are described in Table 6-1.

Table 6-1 List of parameters associated with a general bi-level optimisation problem

Symbol	**Description in a generic bi-level context**	**Description in the context of this study**
F_1& F_2	Objective functions of the upper-level decision maker (system manager)	The total costs and disruptions resulting from the completion of the street works schemes within a planning period
u	Decision vector of the upper-level decision maker (system manager)	Decision variables related to undertaking street works schemes (start times of the schemes, sequence of link closures, type of traffic management arrangements, etc.)
G	Constraint set of the upper-level decision vector	Constraints relating to the scheduling of the street works schemes planned in the network (e.g. earliest start times allowed for the schemes, and latest allowable completion dates)
f	Objective function of the lower-level decision makers (i.e. travellers)	Travellers' objectives: seeking to minimise their own travel times, or travel costs under degraded network conditions (associated with Wardrop's User Equilibrium; alternative assumptions may be selected).
v	Decision vector of the lower level decision maker (travellers)	Traffic flows on the degraded network during the implementation of street works schemes

Symbol	Description in a generic bi-level context	Description in the context of this study
g	Constraint set of the lower-level decision vector	Constraints relating to the traffic assignment function and project optimisation scheduling model
H	The traffic network subject to configuration alterations	The traffic network subject to capacity alterations due to street works activities

Once the type of the optimisation problem of this study is established, its characteristics can be identified by reviewing other similar types of optimisation models. The characteristics of bi-level type of optimisation problems are reviewed in the following section.

6.2. Characteristics of the resulting bi-level optimisation problem

6.2.1. Identifying similar optimisation models in transport studies

The literature review identified the *work zone optimisation problems* (e.g. Chen and Tang, 2012; Chien and Tang, 2012, Kendli et al., 2010) as the most relevant class of transportation modelling studies to the topic of this research. A *work zone* is defined in the (American) Highway Capacity Manual (Transportation Research Board, 2000) as "an area of a highway in which maintenance and construction operations are taking place that impinges on the number of lanes available to traffic and affect the operational characteristics of traffic flowing through the area."

The main characteristic of work zone optimisation studies is the fact that they evaluate the trade-off between two conflicting costs, namely highway maintenance and construction costs, and the costs incurred by the travelling public. A model which is able to evaluate this trade-off can then be used to optimise the decision and design parameters such as the dimensions and configurations of work zones, and durations and allocated resources of the street works schemes. These optimisation models also deal with a range of external variables and constraints such as varying hourly and daily traffic volumes, available construction resources, limitations for work zone dimensions, etc. A good example of such models relate to the PhD thesis by Yang (2010) who developed two optimisation models for minimising the costs of highway maintenance works for a multiple-lane two-way highway.

- A model for evaluating *short-term* impacts of work zone decisions, which seeks to minimise the total work zone agency costs and travellers' costs.

- A model for evaluating *long-term* impacts of work zone decisions. This model incorporates long-term impacts over the pavement maintenance life cycles and seeks to maximise an effectiveness index – associated with a pavement performance model (see, for instance, Gu et al., 2012 for the underlying theories) - over a planning horizon. The agency costs and user costs were embedded in the aforementioned effectiveness index developed by him in his thesis. The decision variables include:
- The number of work zones
- The starting time and ending time of each work zone
- The index of the selected traffic management option alternatives (e.g. type of lane closure arrangement, work rate option, and detour strategy employed in each work zone)

The optimisation problems developed in his study were subject to a series of operational and traffic impact constraints such as project deadlines and maximum acceptable queue lengths.

The modelling work of Lukas and Borrmann (2011) is another example of optimising infrastructural maintenance activities to deal with finding an optimum schedule of maintenance works on the *infrastructural buildings* (mainly bridges and tunnels) of an urban transportation network. For their optimisation problem, they specified a range of constraints such as the latest maintenance time for each bridge before it is deemed unsafe, budgetary constraints, and the fact that blocking of arterial roads and urban freeways should be minimised by trying to conduct the maintenance works of all buildings on an arterial road or urban freeway simultaneously.

The focus of their scheduling optimisation problem was to find the optimum schedules of maintenance works in such a way that the total increase of network travel times due to road closures are minimised. The authors developed a meta-heuristic optimisation algorithm based on the *ant colony optimisation* methodology (first developed by Dorigo, 1992) for finding the optimum solutions.

In their paper, they presented the experimental results of running the optimisation model for a network with 100 streets, each street having a bridge which is due for maintenance in the next 15 years. It was assumed that maximum 10 bridges could be maintained each year, and the maintenance of each bridge would take one whole year, whilst during this period the capacity of the affected links would be degraded by 50%. To measure the annual changes in the level of origin-destination flows due to varying conditions of the network links, they ran the traffic assignment model for each year, i.e. 15 times in total.

For the street works optimisation model developed in this thesis, however, the number of times which the traffic assignment model needs to be executed for degraded network conditions is likely to be substantially higher than what was required for the model of Lukas and Borrmann (2011). This is to enable the optimisation algorithm to capture the effects of *daily* flow fluctuations, as well as varying network link capacities (due to traffic managements required for street works), on the road users' travel times.

6.2.2. Solution to the lower level optimisation problem

The lower level of the optimisation problem of this study is normally concerned with finding traffic flow levels in the network under degraded conditions. For complex schemes, it may also be required to solve a project optimisation model (see section 6.7) to find the optimal values of resources which are required for undertaking a scheme.

solving the **lower** level optimisation problem is only important because it helps with solving the higher level optimisation problem. The optimum values of the lower level optimisation variables per se are not usually important to the decision makers.

For very small networks with a few numbers of nodes, links and origin-destination routes, it would be reasonably easy to formulate the Wardrop's User Equilibrium and find the equilibrium travel times by using an appropriate solution algorithm such as the Frank-Wolfe method (1956). It is reminded that a short review on traffic assignment and user equilibrium theories, including those most suitable for degraded network conditions and their solution algorithms, was presented in chapter 3.

With realistic size networks, however, it will be advantageous to use a traffic assignment package which provides a range of options for different types of inputs, route choice models, and additional analysis needs. This, for instance, includes taking into consideration the effects of junctions and traffic lights (through complementary simulation programmes), multi-class travellers (i.e. travellers with different values of time), and different types of user equilibrium assumptions. The algorithms embedded in such packages have normally gone through various improvements over the years to provide more robust results, and cater for more realistic circumstances. A number of such traffic assignment packages are: SATURN (Van Vliet et al., 2015), OMNITRANS (DAT.Mobility, 2014), CONTRAM (TRL, 2014), DIADEM (Atkins, 2011), NEXTA & DTALite (Zhou et al., no date), CORSIM (University of Florida, 2014) VISSIM (PTV Group, 2014), and DYNASMART-P (Federal Highways Administration, 2014).

For the optimisation model of this study, the interaction between the main optimisation function of the model (higher level problem) and the traffic assignment package (lower level problem) is shown on Figure 6-2.

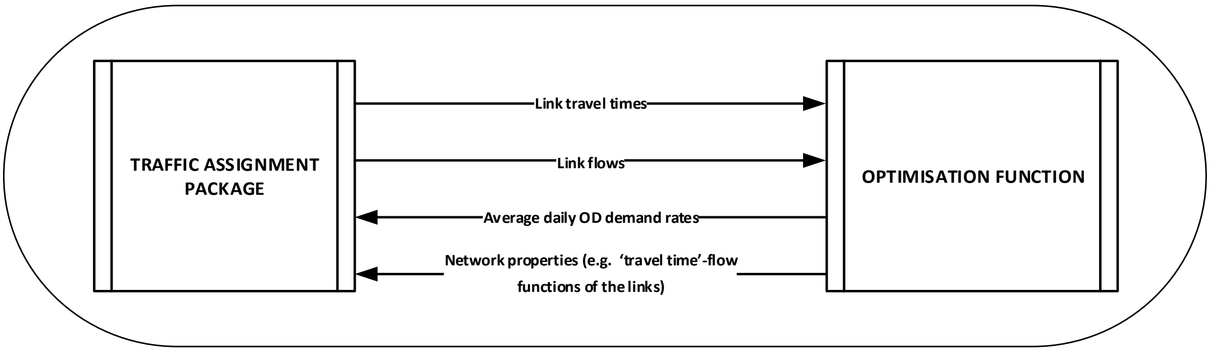


Figure 6-2 Interaction between the optimisation function and the traffic assignment programme

The interaction shown on Figure 6-2, however, can give rise to a major issue for the higher level optimisation function during its progress: This is associated with the amount of time required for the traffic assignment package to complete a run in order to calculate link travel times, and provide them to the higher level optimisation function:

The literature review has shown that for at least two other well-known classes of network studies, namely network vulnerability assessment models and some types of work zone optimisation problems, this issue has been encountered too. For instance it is quoted (Chen et al., 2012) that for vulnerability assessment of the well-known Chicago regional network, consisting of 39,018 links (Dial, 2006), the run time for the traffic assignment model would be about half an hour. Therefore in order to evaluate the vulnerability of the network by using a full scan approach (see section 3.2.3.2), it can take about two years to identify the most critical links.

In order to minimise the running time of the algorithm, the number of times which the traffic assignment model is called from the upper level problem will need to be minimised. Also, it can be advantageous to run the traffic assignment model only on a smaller part of the network where degradation of a nearby link is expected to cause noticeable effects. For instance in their *network vulnerability analysis* work, Chen et al. (2012) propose an *impact area* vulnerability analysis approach to evaluate the consequences of a link closure within its impact area instead of the whole network. They define the impact area of a link a, denoted by $G_a = (N_a, A_a)$, as a sub-network of the whole network G where N_a and A_a are the set of nodes and the set of links adjacent to a link respectively. Subsequently they developed a process for deducing the impact area of a link (denoted by G_a). Adopting this approach, the time required to find the impact of a link closure within its own impact area is significantly less than that pertaining to running the traffic assignment of the whole network.

Gemar (2012) presented an *automated sub-network selection* process in order to use dynamic traffic assignment models for evaluating the impacts of traffic network modification scenarios. He highlights the prevailing trade-off between improved efficiency and reduced accuracy associated with using sub-networks – instead of a full scale network analysis - for running traffic assignment models. However, he concludes that the choice of a sub-network may be dependent on what questions the analyst would like answered, for instance the effects of the selected traffic management options on a particular portion of the network which is of more significance to the analyst. Therefore, his research concludes that engineering judgement remains an important part of the sub-network selection and analysis process (this is somehow equivalent to adopting a *manual* sub-network selection approach).

Most recently, Zheng et al. (2014) applied a *k-shortest path algorithm* for their work zone scheduling problem to identify several alternative routes for each work zone link, and then shift traffic flows to these diversion routes in such a way that travel times along the alternative paths are equal. Their approach is based on the behavioural assumption that most traffic rerouting is restricted to divert at *d* miles ahead of the work zone street and merge *d* miles downstream (where *d* is selected through expert judgement).

In practice and as part of the planning arrangements for street and highways maintenance works, it is common to divert the drivers affected by the traffic management restrictions onto pre-allocated diversion routes. The diversion routes are selected in such a way that the additional diverted traffic will not cause significant delays to the existing users of those diversion routes. This is achieved by ensuring that the capacity of the relevant links and the timing of the diversions are suitable to accommodate the additional diverted traffic. Expert judgement can be used to predict the proportion of the traffic diverted to each diversion route.

Using such arrangements which suit many real cases of highways and street works, there would be no need to run the traffic assignment model for the entire network and for every degraded condition during the optimisation process. Instead, the traffic delay costs can be worked out by knowing the proportion of the diverted traffic from one route to another.

6.2.3. Solution to the higher level optimisation problem

In bi-level optimisation models, the optimum values which are obtained by solving the **lower** level optimisation problem are only important insofar as they help with solving the higher level optimisation problem. On the other hand solving the **higher** level optimisation problem is equivalent to solving the entire optimisation problem, and is concerned with finding optimal values for the decision parameters which are of main, if note sole, interest to the planners in relation to implementing the underlying improvement schemes in the network.

Bi-level mathematical programmes are known to be difficult to solve, because evaluating of the upper-level objective function requires solving the lower-level sub-programme (Chen et al., 2010). As such, solving the optimisation problem was set as the second objective of this research, and is dealt with in chapter 7.

6.3. Graphical representation of the decision making problem associated with optimal scheduling of street works schemes

Once the general form of the optimisation problem of this study was expressed as an established type of mathematical optimisation model, it was important to identify all of its elements and their relationships with each other. This mainly includes all underlying input and output variables, different functions embedded in the model, and their relationships with the variables and objective functions of the model. For doing so, a good practice is using an *influence diagram* which is a network representation of probabilistic and decision analysis models (see, for instance, Shachter, 1988).

For the purpose of analysing the problem of this thesis, a simplified version of this diagram to suit deterministic problems is adopted. This entails using a number of cloud symbols and arcs (arrows) for referring to different elements of the underlying problem:

- **Uncontrolled inputs or chance variables:** for instance variations in travel demands, cost of traffic management options, etc.
- **Controlled inputs or decision variables:** these associate with the variables which are subject to optimisation.
- **General variables:** these are the variables which should be calculated by the optimisation model in order to measure the effects of street works schemes (see the following item).
- **Objectives of the problem:** these relate to the quantitative and qualitative effects of street works schemes which should be minimised by the optimisation model.

In order to build the causal diagram for the optimisation model of this study, the following steps are followed:

1. The decision variables, chance variables, and general variables of the optimisation model are identified with appropriate cloud symbols.

2. The relationship between the decision variables, chance variables, and the general variables are shown on the diagram with arrows.
3. The *sub-objectives* of the optimisation model are shown on the diagram with appropriate cloud symbols. The sub-objectives relate to the itemised costs and effects which should be later accumulated, when possible, to form the main objective functions of the optimisation model.
4. The relationship between the general variables and the sub-objectives are shown on the diagram with arrows.
5. Finally the sub-objectives are attributed to the main objective functions of the optimisation model (i.e. those established in chapter 5).

The results of the above process is shown on Figure 6-3 which is the graphical illustration of the components of the optimisation problem studied in this thesis. The next sections of this chapter deals with describing the remaining elements of the optimisation model which are shown on Figure 6-3.

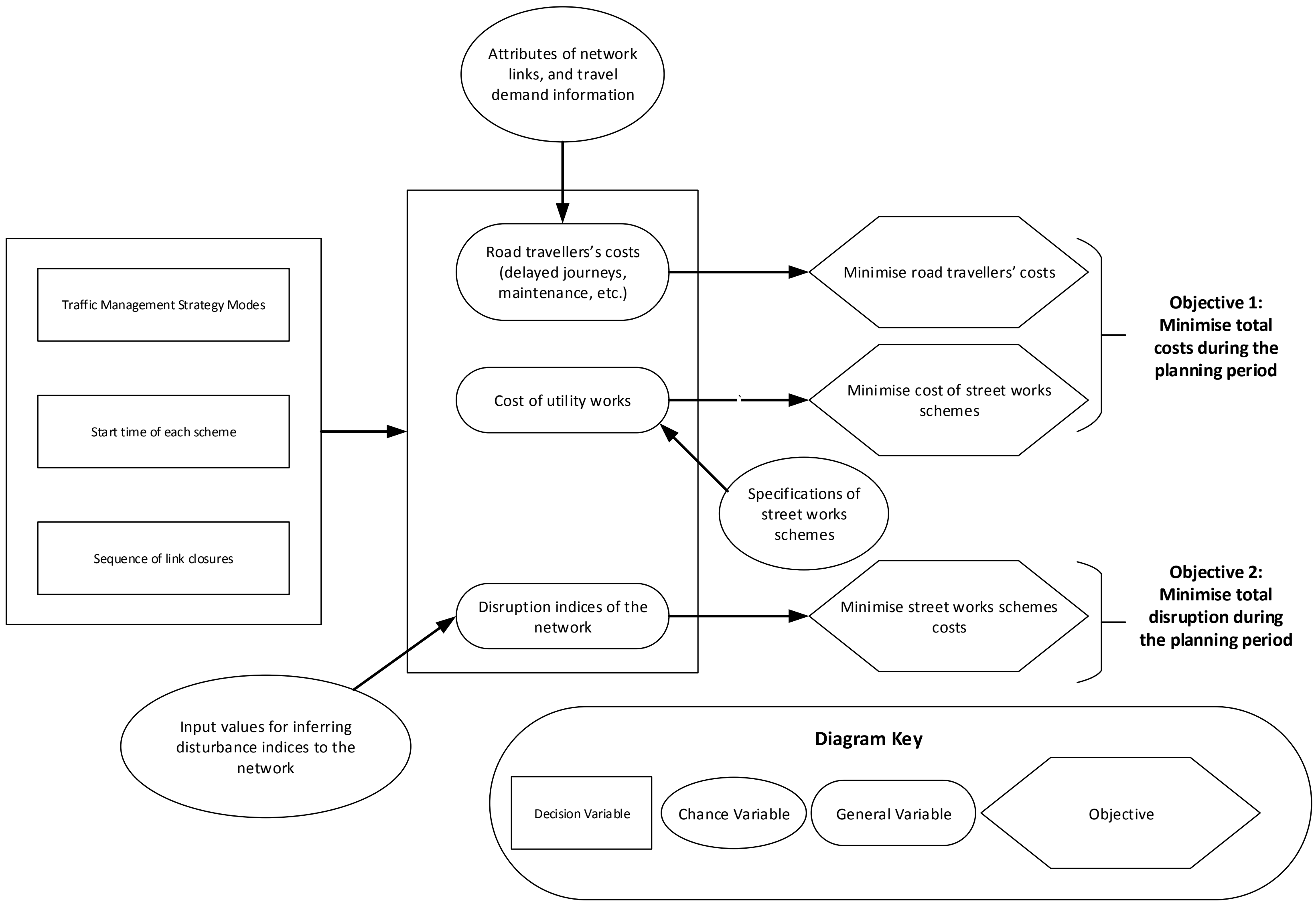

Attributes of network links, and travel demand information
Traffic Management Strategy Modes
Start time of each scheme
Sequence of link closures
Road travellers's costs (delayed journeys, maintenance, etc.)
Cost of utility works
Disruption indices of the network
Specifications of street works schemes
Input values for inferring disturbance indices to the network
Minimise road travellers' costs
Minimise cost of street works schemes
Minimise street works schemes costs
Objective 1: Minimise total costs during the planning period
Objective 2: Minimise total disruption during the planning period
Diagram Key
Decision Variable
Chance Variable
General Variable
Objective

Figure 6-3 Graphical representation of the components of the optimisation model

6.4. Inputs and outputs of the optimisation model

As a result of the components which form the optimisation model of this study, the following **inputs** should be provided to the optimisation model:

- Time-varying travel demand matrix to provide average daily traffic rates between all origin-destinations of the network
- Attributes of network links such as their cost-flow or 'travel time'-flow functions.
- The input variables and parameters for the fuzzy inference systems discussed in chapter 5 in relation to deducing the disturbance indices which were developed for measuring origin-destination and link accessibility related disturbance to network users (section 5.2.4).
- Details of the street works schemes which are planned for implementation during a planning period (assumed to be a calendar year). This, for instance, includes the latest allowable completion dates for each scheme, relationship between durations of the schemes and the traffic management options available for a link, and any opportunities for undertaking two or possibly more schemes at the same time for some links.

The **outputs** which are to be obtained from the optimisation model include: the preferred start times, traffic management options, and sequence of link closures for every street works scheme which is due to be undertaken during the planning period.

The type of input and output variables of a street works scheduling problem can vary from one case to another, due to reasons such as the external constraints, and nature of the schemes. In chapter 9 (see section 9.4) several other types of variables which could be subject to optimisation by a street works scheduling model have been identified.

6.5. Modelling traffic demand fluctuations

As reviewed in chapter 2 in relation to network design problem studies, minimising the impacts of street works schemes on road travellers' journey times is normally the most important consideration when deciding on changing the configuration of a network on a temporary or permanent basis (e.g. traffic management schemes for street works, and road capacity improvement schemes). Securing the safety of the working crew and members of the public, in terms of allocating sufficient working area and safety margins during the works, is another key consideration,

In some circumstances, it can be sensible to completely suspend a street works scheme once it has started in order to avoid causing excessive delays to road travellers at peak hours or days. This is the reason for embedding an additional type of variable to represent the duration of the idling periods within work zone optimisation models (see, for instance, Chien and Tang, 2012; Yang, 2010).

As such, understanding the pattern and variation of traffic flows at different times of the day and days of the year is quite important for planning street works schemes. There can be a range of sources for causing variation in traffic demand. The most common ones, highlighted by Brennand (2011), are:

- commuters' travelling (normally morning and evening peak hours)
- Special events (Lomax et al., 2003)
- random fluctuations
- business or recreational or other cyclic activities on certain days of the week (Ruimin, 2004; Margiotta, 2002)
- Change in proportion of HGVs (Cheu et al., 2007)

Ukkusuri and Patil (2009) noted that the traditional methods of estimating traffic flows are based on studying past trends, and using deterministic point estimates. These methods are deemed unsuitable for planning major improvement schemes which should consider many years in the future. This is because they result in sub-optimal decisions (Ukkusuri and Waller, 2006), and the resulting estimates are often risk-prone, and can lead to significant economic losses (Goetz and Szyliowicz, 1997; Flyvbjerg et al., 2005). To deal with the uncertainties in the level of traffic demand, Patil and Ukkusuri (2007) used a stochastic process whereby the demand is modelled as a stochastic process (e.g. using a Geometric Brownian Motion (GBM) or a Mean Reverting Process (MPR)) over the planning horizon. This approach is referred to as *longitudinal demand stochasticity* (two other classes of demand stochasticity models are provided in Ukkusuri and Patil (2009) for optimising transportation investment decisions).

In comparison with planning major transport infrastructure schemes, a scheduling exercise of street works schemes is normally undertaken for a much nearer time in the future. Hence, the uncertainties and risks of inaccurate estimates are expected to reduce significantly, therefore making it very reasonable to use existing traffic counts data and traffic growth prediction rates.

Forecasting future traffic flows is regarded as an independent subject (for the underlying theories, see Ortuzar and Willumsen, 2011), and is not in the scope of this study. Rather, the predicted traffic flows for all origin destination of the network within the planning period should be calculated in advance, and made readily available to the optimisation model during an optimisation run. This approach has been adopted in most other similar optimisation models, not least work zone optimisation studies which have been reviewed in this thesis.

6.6. Deducing the amount of delays incurred by road-users due to street works schemes

For the travellers of a given origin-destination, the delays due to undertaking street works schemes are the difference between their journey times under degraded conditions, and those under normal (i.e. un-degraded) conditions.

Link travel time functions are commonly used to deduce the travel times incurred by the traffic on a given link of a network. They are defined as functions which postulate the relationship between the travel time on a road, and the volume of traffic on that road (Rose et al., 1989).

A commonly used type of travel time function is that proposed by the US Bureau of Public Roads (1964) - known as the BPR travel time function – which is of the following form for a given link:

$$t_a = t_{oa}(1+\alpha(f/c)^{\beta}) \qquad \text{(Eq 6.2)}$$

where f refers to the traffic flow on the link, c and t_{oa} are the capacity and the free flow link travel time, and α and β are parameters with initial suggested values of 0.15 and 4 respectively. When appropriate, a link can poses different link travel time functions based on factors such as the number of lanes open to the traffic, and the time-varying speed limit set for that link.

Traffic related standards such as Chapter 8 of Traffic Signs Manual (Department for Transport, 2009f, p.32) have recommendations for the throughput of a lane based on type of the road, the width of the road (e.g. narrow or wide roads), and percentage of heavy goods vehicles. Such information can assist with choosing appropriate values for travel time functions in order to measure journey times under degraded network conditions.

Other methods for deducing link travel times have been observed using neural networks (e.g. X. Zeng and Zhang, 2013), whole-link travel time functions (e.g. Friesz, 1993; Carey et al., 2003), fluid flow (e.g. Lighthill and Whitham, 1955), cell transmission models (e.g. Daganzo, 1995), micro-simulation methods by using a car-following model (e.g. General Motors' car-following theories explained in May, 1990, pp. 162-181), and fuzzy logic (e.g. Rudjito, 2006).

In comparison with BPR type of functions, most of the above models promise to provide more accurate values for link travel times, particularly in dynamic situations (see section 3.1.6), by capturing a higher number of influential factors which may impact on the time it takes for a vehicle to travel along a link. However more advanced models are normally more complex and require more data, computational power and execution time.

Further models, such as the spreadsheet based INCA (Incident Cost Benefit Analysis) which was developed by Mott MacDonald (2000) and quoted in Robinson (2005), have been observed for deducing delays caused as a result of *road incidents.* These models, however, may be applicable for some type of traffic management arrangements suitable for undertaking street works schemes (e.g. for a short length of lane closure on a long link of the network).

Watling et al., (2012b) report on the empirical study they conducted to evaluate how well a traffic equilibrium model would predict real network impacts affecting road capacity. As part of their study, they developed the following four step process which they are advocating to traffic agencies in relation to using analytical models for predicting journey delays during capacity degradation events in traffic networks.

(a) Identifying (in advance) a planned network disruption, e.g. due to road or utilities maintenance, that is likely to have a significant impact on congestion and route choice.

(b) Designing a registration plate survey to monitor routing patterns before, during and after the disruption.

(c) Comparing the before-and-after data with the predictions of a network equilibrium model, subsequently adjusting the network model so as to reflect the empirical findings.

(d) Periodically repeating steps (a)–(c), reflecting additionally on the consistency of findings from step (c) over time.

Overall, it transpires that the most suitable options for calculating delays to road users can vary from one case to another, depending on factors such as complexity of the situation, amount of data available, and the reasonable trade-off between the accuracy, and speed and cost of running a model. In practice, however, BPR type functions remain the dominant method for deducing link travel times, including delays to road users, due to their simplicity and also because they are embedded in the most commonly used traffic assignment programmes such as SATURN (Van Vliet, 2011).

6.7. Formulation of street works schemes to interact with the optimisation model

The term *street works* in this study, as first explained in chapter 1, is defined in a very broad context to cover all planned activities which, once implemented, can reduce the capacity of the links of a traffic network. When street works activities are undertaken in a planned and coordinated way – which is a requirement for all non-emergency works (see chapter 2) – they are commonly referred to as street works *schemes.* Nonetheless many emergency works schemes can be regarded as street works schemes too, since they are likely to be undertaken based on contingency plans developed beforehand.

In such a context, street works schemes are similar to other construction and maintenance **projects** which are scheduled in advance to work out their costs, completion times, best sequence of project tasks, etc. based on a series of input variables and constraints.

The duration and completion costs of street works schemes are two important parameters which should be calculated by the optimisation model of this study during the evaluation of different scenarios. Similar to analysing other types of projects, these parameters are dependent on the *resources* allocated to the schemes, including the level of labour and equipment, and the amount of working space available for the works.

The literature review identified a subject within the project management theories which deal with developing *project optimisation scheduling models*, or in short: *project scheduling models*. These models are referred to as *resource-constrained project scheduling problems* or RCPSP (Wuliang and Chengen, 2009) and include a well-known type of problem, namely the discrete time/cost trade-off problem (DTCTP) which was first introduced by Hindelang and Muth (1979).

The following formula shows the general objective function of the DTCTP, associated with minimising the total cost of a project (scheme), which was studied by Wuliang and Chengen (2009):

$$F_c = \sum_{i \in V} \sum_{m \in M_i} \left(x_{im} . y_i . \sum_{k \in K_{im}} (ed_{im} . c_k) \right) + \sum_{i \in V} (u_k . f_n) \qquad \text{(Eq 6.3)}$$

Table 6-2 describes the variables used in the above formula:

Table 6-2 List of variables in the general objective function of the project scheduling problem (DTCTP)

F_c	total cost of the scheme (project)
V	Project activities
M_i	Activity modes for the project activity *i*
k	a *renewable*[1] resource
d_{im}	Duration of an activity *i* when activity *i* is performed in mode *m*
ed_{im}	crashing duration when activity *i* uses resource k in the *crashing way*[2]
f_n	the finish time of the end activity
c_k	direct cost per unit time of k when k is used in crashing way
x_{im}	decision variable, equals 1 if activity *i* is performed in mode m and 0 otherwise
y_i	decision variable, equals 1 if activity *i* is performed in crashing way and 0 otherwise
u_k	cost per unit time of k
m	resource mode
Table notes: 1. Project resources are usually categorised as *renewable* (e.g. manpower resources) and *non-renewable* (e.g. machinery). 2. An activity can be executed in *crashing way* whereby its duration is shortened by spending project direct costs.	

A DTCTP optimisation model seeks to find those values of the decision variables x_{im} and y_i which results in minimising the above objective function.

The DTCTP is known to be a NP-hard problem (Prabuddha et al., 1997), and difficult to be solved in some cases (Deineko and Woeginger, 2001). Therefore in their study Wuliang and Chengen (2009) proposed a meta-heuristic genetic algorithm solution for solving the multi-mode DTCTP.

DTCTPs are quite familiar to project planners and have been formulated in such a general way to be applicable to a wide range of projects. Therefore this study recommends to use a DTCTP formulation in order to deduce the relationship between the available resources to a street works scheme duration of the scheme, and the total cost of the scheme. This is referred to as '*the formulation of street works schemes'* in this thesis.

For the optimisation problem of this study and without undermining its generality, the entire works related to a single scheme on a link is regarded as one single activity within the project scheduling formulation. This approach is quite suitable for street works activities conducted in urban environments where normally only one working area is available at a time on a link.

The link capacity available to the utility companies (e.g. either the whole area of a given link or half of the capacity of that link) is represented by an integer number *m* which is a *resource mode* – or in short just *mode* - by which a street works scheme is undertaken. An additional mode, accepting integer numbers, will be used to represent the traffic management strategies selected for the links. When appropriate, the number of these modes may be expanded to account for other options such as undertaking schemes during the day or overnight, number of working hours for a shift, and even the number of working areas on a link (e.g. multiple work zones).

When the values of the above modes are limited to only a few options, which is normally the case with most street works schemes in urban environments, it would be sensible to combine these modes to deduce a single *combined mode*. Consequently the cost and duration of a street works scheme for each link of the network can simply be deduced and passed to the optimisation model as a function of the value of this combined mode. For instance the experimental tests provided in chapter 8 will use a combined resource mode variable with only two feasible values for undertaking a scheme for each link of the network.

This formulation has an additional benefit for circumstances where an opportunity exists for conducting two or more different street works schemes for a link at the same time (e.g. using a trench sharing scheme mentioned in section 2.5.1) . In such a case, *m* would be allowed to accept another integer value, say *m=k*, associated with the joint road space occupation condition. Subsequently the costs and durations of the simultaneous works can be calculated as a function of the *m=k* once they coincide with each other for a network link during the optimisation algorithm runs (these scenarios would have been otherwise ruled out by the optimisation algorithm due to the rise of a conflicting condition).

The process described above, which is referred to as *'formulation of traffic management options'*, is illustrated on Figure 6-4.

Figure 6-5 illustrates the overall formulation of street works schemes to interact with the optimisation algorithm which was introduced earlier in this section (the optimisation algorithm will be explained in detail in chapter 7).

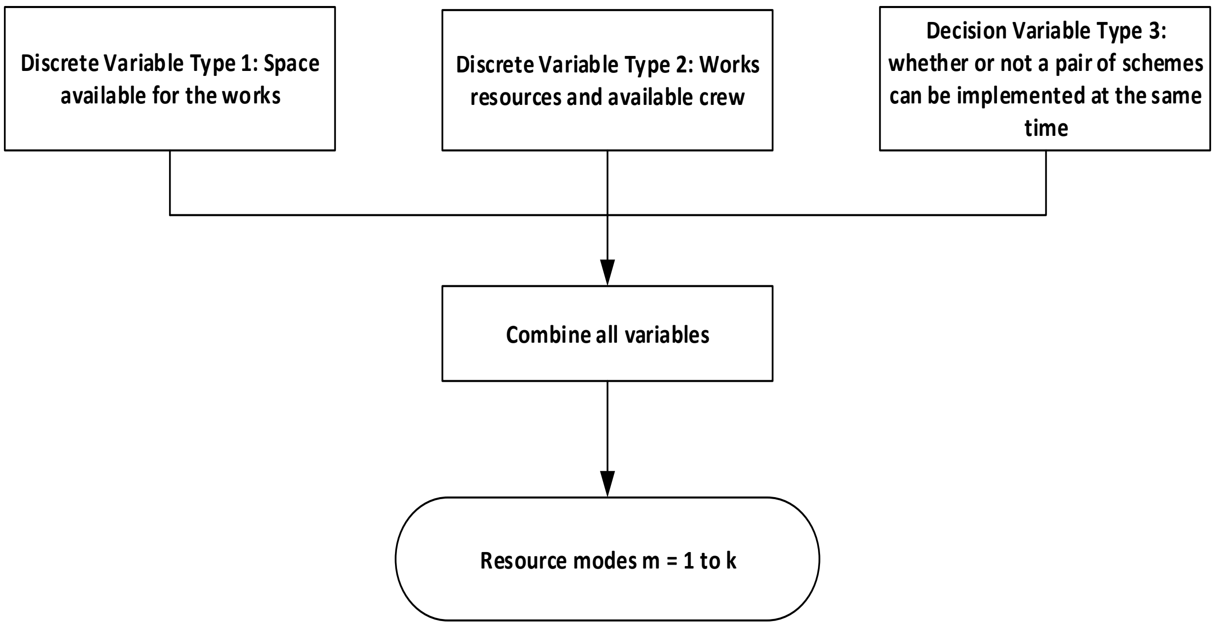


Figure 6-4 Formulation of traffic management strategies using a combined resource mode

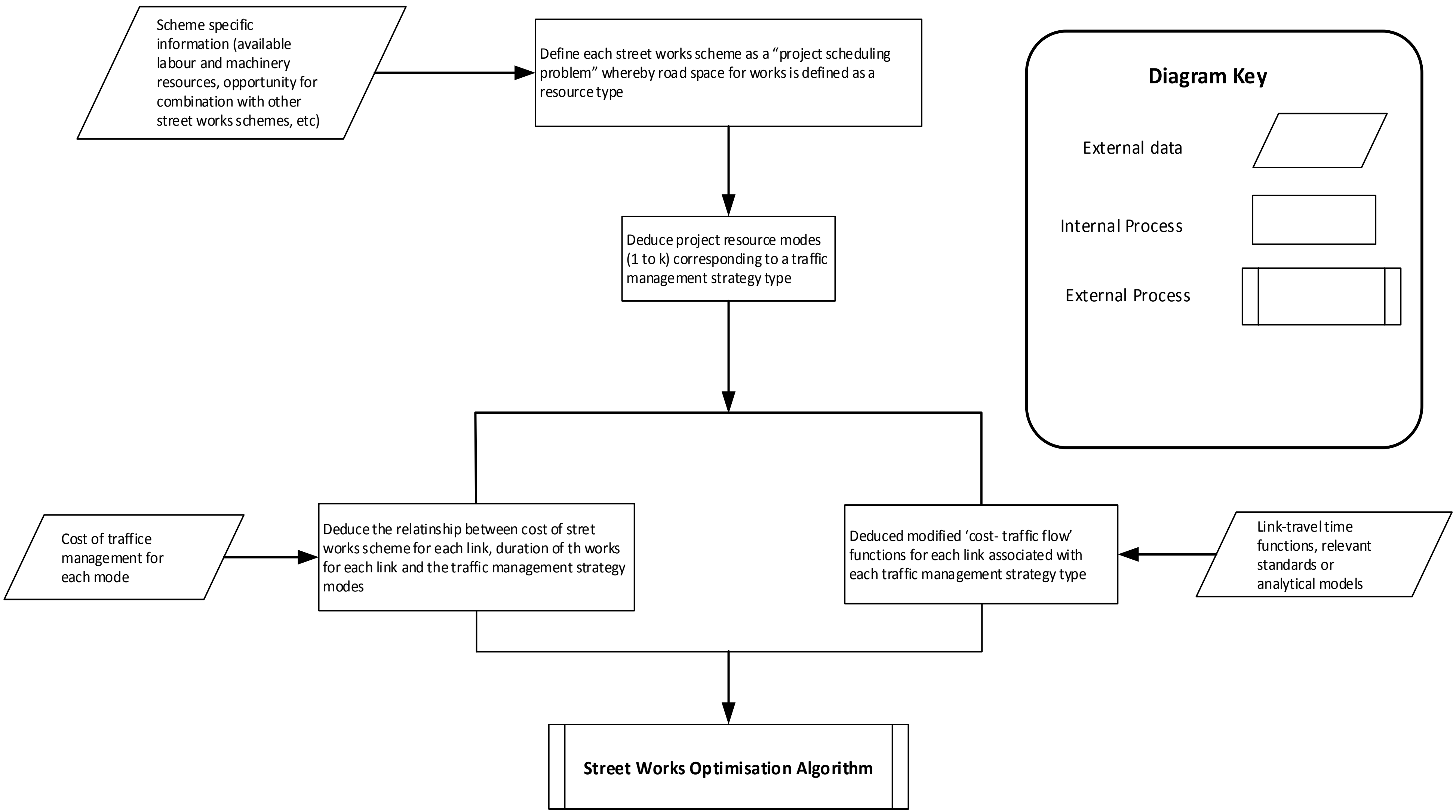


Figure 6-5 Formulation of street works schemes to interact with the optimisation model

6.8. Chapter concluding remarks

This chapter was initiated to explain the development of the optimisation model of this study.

First, the optimisation model was formulated as a bi-level programming mathematical optimisation problem which is well-known and sufficiently studied in transport studies. Subsequently the underlying elements and functions embedded in this optimisation model were formulated and described. In particular, street works schemes were formulated as a general type of project scheduling model to enable deducing the duration and cost of a street works scheme for every link of the network subject to a scheme, based on the values of the relevant input variables.

The work undertaken in chapter 5 and 6 has led to developing and establishing all of the underlying elements of the optimisation model and the way they interact with each other. This has been essential for developing a suitable solution algorithm for the optimisation problem, which is studied in the next chapter of this thesis.

Chapter 7
Description of the Proposed Genetic Algorithm Solution

In this chapter, first the need for using an optimisation algorithm to solve the problem of this study is established (section 7.1). Next from section 7.2 onwards, the formulation and properties of the proposed genetic algorithm solution are explained in detail. In particular, this includes coding of the genes, adapting the genetic algorithm methodology to suit the discrete optimisation problem of this study, crossover and mutation operations, and the fitness function of the optimisation algorithm.

7.1. Enumeration of the number of possible scenarios for implementing a series of street works schemes

The discrete optimisation problem which is studied in this thesis has a space of finite but often very large number of possible scenarios which are theoretically feasible for undertaking a given number of schemes in a traffic network, and during a planning period. For a scheme which is due for implementation on *n* number of links of a network, the total number of theoretically feasible scenarios, represented by $\boldsymbol{E_i}$ (*i* is the index of a street works scheme), can be enumerated by following the steps which are described below (assuming work on each link constitutes a single scheme):

Step 1: the first link is selected; this can be done in *n* different ways

Step 1+*i* *(i=1 to n-1)*: from the remaining links, another link is selected which is possible in *n-i* ways (*i* = 1 for the second round of link selection). Therefore in total *(n-i)* cases are available.

The above process (Step 1+*i*) is repeated until selection of the last remaining link (*i*=*n-1*) to result in the final 'Step *n*'

By following the above procedure, the total number of available scenarios can be calculated from the following formula:

$$E_1 = n \times (n-1) \times (n-2) \times \cdots \times 1 = n!$$

If the scheme on each link can be carried out with two alternative construction modes, the number of possible scenarios will increase further by a coefficient of 2^n , i.e. $E_1 = 2^n \times n!$ (Eq 7.1)

For instance for a street works scheme to be implemented on 50 links, the total number of available scenarios will be:

$$E_1 = 2^{50} \times 50! = 3.42432 \times 10^{79}$$

The result of the above formula expands extremely fast as the value of *n* increases.

This formula calculates the available scenarios for a single street works scheme. With more schemes planned in the network, the space of all theoretically feasible scenarios increases substantially further. The total number of available scenarios can be calculated as the product of the total scenarios deduced for each scheme (e.g. $E_1 \times E_2$ for two street works schemes).

It is however appreciated that in practice there are various constraints and requirements (e.g. the available resources to schemes undertakers, avoiding conflict between two schemes, etc.) which will limit the number of practical scenarios for the implementation of a street works scheme. Nonetheless for realistic size networks, examining every single scenario (i.e. an *exhaustive search* approach) is not possible. Therefore it will be necessary to develop an effective optimisation algorithm in order to find the most desirable scenarios within the available space of all candidate solutions.

7.2. Introduction to the proposed genetic algorithm solution

Bi-level mathematical programmes are *NP-hard* (which is a property studied in *computational complexity theory*; see Arora and Barak, 2009) and many of them are *non-convex* (Miandoabchi and Farahani, 2011). Therefore they are difficult to solve by standard optimisation models such as *branch and bound* or *enumerative algorithms*, since such models could only be applied to optimise bi-level optimisation problems for small networks.

In such cases *meta-heuristic* algorithms such as *genetic algorithms*, *simulated annealing*, *ant colony optimisation*, *differential equation*, *tabu search*, or a combination of them - known as *hybrid meta-heuristics* - have been utilised with success in many transport modelling studies (Luke, 2009). A few examples are:

- **Tabu search** for vehicle routing problems (e.g. Cordeau et al., 2001)
- **Hybrid meta-heuristics** for route optimisation transport studies (e.g. Jing et al., 2012)
- **Simulated annealing** for work zone optimisation studies (e.g. Yang, 2010)
- **Ant colony optimisation** for planning of infrastructural activities (e.g. Lukas and Bormann, 2011)

- **Genetic algorithms** for scheduling of highway work zones (e.g. Chien and Tang, 2012)

Yin (2000) explains that among the above methods, it appears that genetic algorithms have been applied to a wider variety of problem domains including engineering, sciences, and commerce: This is due to their simplicity, minimal problem restrictions, global perspective and implicit parallelism.

Genetic algorithms (referred to as *GAs* in the following list) are search and optimisation procedures motivated by natural principles and selection (Goldberg, 1989), and are different from the majority of other optimisation and search procedures in the following ways:

- GAs work with a coding of the parameter set and not the parameters themselves.
- GAs search from a population of points, not a single point. The traditional point-to-point method is prone to locating false peaks in *many-peaked* search spaces. By contrast GAs work from a rich database of points (a population of strings), simultaneously climbing many peaks in parallel: thus the probability of finding a false peak is reduced over methods that go point-to-point.
- GAs use payoff (objective function) information, not derivative or other auxiliary knowledge. This characteristic makes a GA a simpler method – in terms of its mathematical format - than many search schemes.
- GAs use probabilistic transition rules, not deterministic rules. GAs use random choice as a tool to guide a search toward regions of the search space with likely improvement.

The desirable features described above have led to the widespread application of genetic algorithms for solving bi-level optimisation problems in various transportation related studies. A few recent examples include:

Optimising alternate traffic restriction schemes in urban traffic networks (Shi et al., 2014)

- Optimising the layout of public bicycle rental stations (He et al., 2014)
- Integrated optimisation of logistic networks (Wang and Feng, 2013)
- Optimum line frequencies of transit systems (Buran and Feyzioğlu, 2013)
- Optimisation of variable speed limits in traffic networks (Yang et al., 2013)

In a genetic algorithm, a population of *strings* (also called *chromosomes* or *individuals*) which are encoded as candidate solutions are gradually evolved towards better solutions. Successful application of the genetic algorithm to solve an optimisation problem to a large extent depends on how well the candidate solutions are coded within the optimisation algorithm. Therefore a section of this chapter will be dedicated to describing the way candidate solutions are coded within the proposed genetic algorithm solution methodology.

It is very common to use off-the-shelf optimisation packages to solve many types of optimisation and scheduling problems in various fields, including transportation studies. MATLAB programming language, developed by MathWorks Incorporation (MathWorks Inc., 2014d), was selected for the coding of the entire optimisation problem of this study. It is a programming language which is widely used in academia and across various engineering and science subjects. MATLAB package includes built-in single-objective and multi-objective genetic algorithm optimisation functions. These functions have the benefit of providing default options for the underlying elements of a genetic algorithm, such as the *population generation function,* and *cross-over* and *mutation operators.* MATLAB genetic algorithm functions also allow for the user to define customised functions for each of these elements with the aim of improving the performance of the optimisation function, or tailoring the optimisation function for specific problems.

Figure 7-1 illustrates where MATLAB genetic algorithm functions are placed within the general structure of the optimisation algorithm which is devised in this study.

The rest of this chapter deals with describing the main elements of the optimisation algorithm, including formulation of the candidate solution chromosomes, fitness function, and mutation and crossover operators. They are however preceded by a section to introduce multi-objective techniques, since the optimisation problem of this study entails minimising two objective functions at the same time.

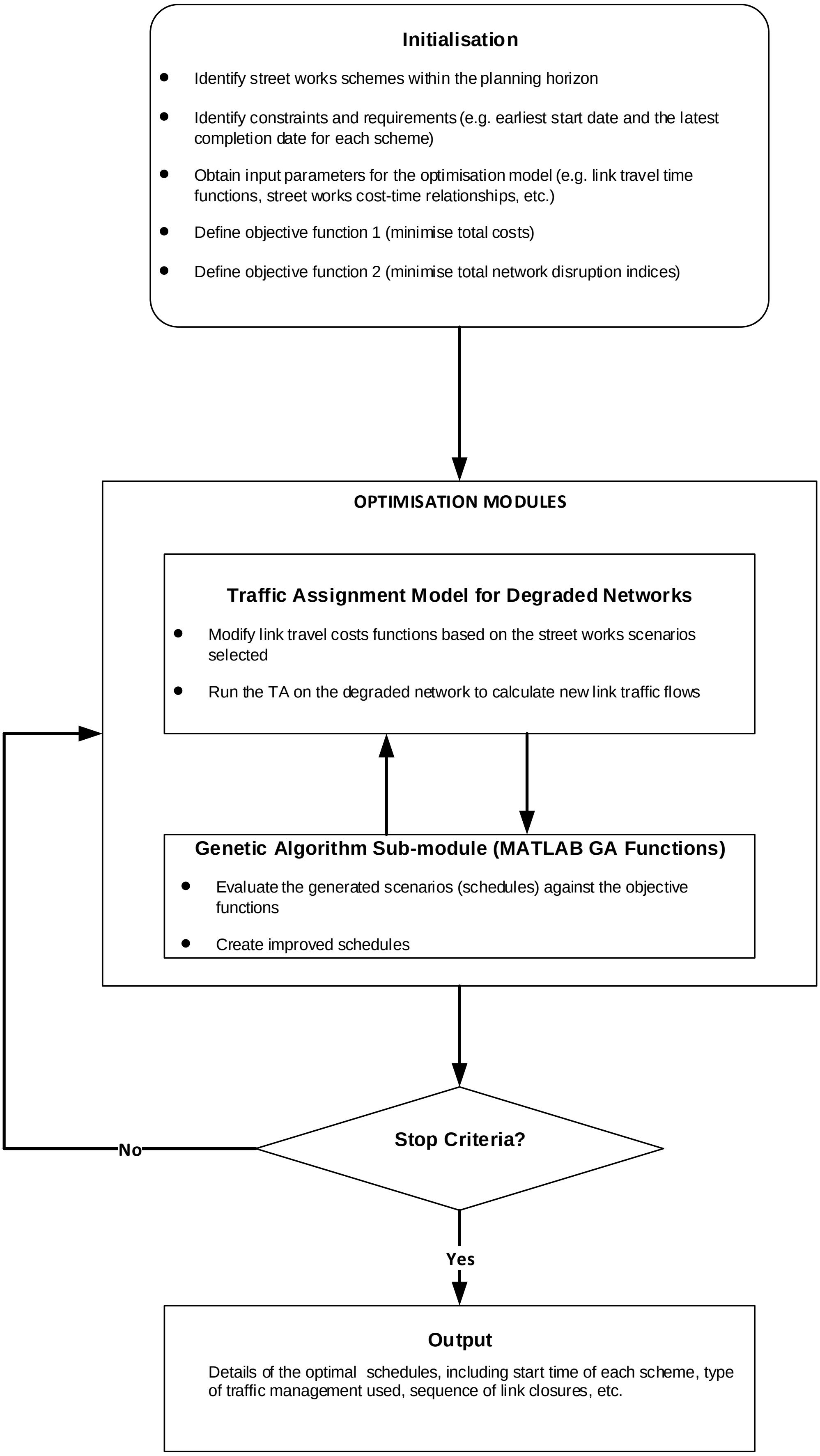


Figure 7-1 The genetic algorithm solution framework for solving the street works optimisation problem

7.3. Selection of a suitable multi-objective optimisation methodology

7.3.1. Introduction to multi-objective concepts and techniques

In practice, many optimisation problems are multi-objective where two or more objective functions are sought to be optimised at the same time. This also applies to the optimisation problem of this study which requires that the monetary costs of the street works schemes (the primary objective function), and the non-monetised disruptions resulting from these schemes (the secondary objective function) are minimised simultaneously.

However the objective functions of a problem may have opposing characteristics, in such a way that what decreases the value of one function may increase the value of another. Arora (2004; p. 548) explains that to clarify what is meant by the *minimum of multiple functions*, the concept of *Pareto Optimality* (Pareto, 1906) has been devised as follows (Arora, 2004; p. 548)

"A point x in the feasible design space S is called Pareto optimal if there is no other point x in the set S that reduces at least one objective function without increasing another one."*

In the context of the optimisation problem of this study, a *scenario* is Pareto optimum if there is no other feasible scenario that can reduce the total costs of street works schemes without increasing the total resulting disruptive effects, or vice versa. The total costs and disruptive effects which are incurred by the stakeholders should be measured for an entire planning period (e.g. one calendar year) by the optimisation model.

Because mathematically there can be infinitely many Pareto optimum solutions for an optimisation problem, a planner often has to make decisions concerning which solution is preferred, through incorporation of how he or she feels about different solution points (Arora, 2004).

The weighted sum method is regarded as the most common approach to multi-objective optimisation (Arora, 2004). It entails combining all objective functions of the problem to a consequent single objective function by using a vector of weights which are provided by the decision maker:

$U = \sum_{i=1}^{k} w_i f_i(x)$ (Eq 7.2) where:

U is the consequent objective function

$\boldsymbol{w}$ is a vector of weights set by the decision maker such that $\sum_{i=1}^{k} w_i = 1$

$\boldsymbol{f}$ is the vector of all objective functions of the problem

By using the weighting factors before the problem is solved, it is possible to generate a single optimum solution. An alternative approach is to obtain the Pareto optimum set first, and then use a multi-objective technique such as the weighted sum method, or *a utility function*, for the Pareto points to choose a single optimum point (a utility function is a mathematical expression that attempts to model the decision maker's preferences).

The weighted sum method, similar to most other multi-objective techniques, allows the objective functions to be formulated into a single objective function first. Subsequently a suitable single-objective optimisation method (e.g. genetic algorithms) should be used to solve the consequent formulation.

Alternative methods to the weighted sum method exist (see Arora, 2004; pp. 556-559). However the decision on which multi-objective optimisation is most appropriate or most effective is very subjective, dependent on the nature of the user's preferences and what type of solutions might be acceptable (Floudas et al., 1999). In chapter eight, the genetic algorithm methodology has been used in conjunction with the weighted sum method in order to produce a set of Pareto optimum points, as well as a single preferred solution, for the experimental tests.

In order to select suitable weight coefficients for the weighted sum method – based on the judgement and perception of the planners - one can use the Analytic Hierarchy Process (AHP) which is developed by Saati (1980). AHP is a multi-objective analysis technique that allows trade-off between multiple criteria with different measurement units. It is a structured technique for organising and analysing complex decisions, based on mathematics and psychology. AHP is widely used in many types of transport-related studies; a few recent examples are:

- Infrastructure investment projects (e.g. Mishra et al., 2013; Zietsman and Venderschuren, 2014)
- Development of 'cooperative vehicle infrastructure systems' (Chu et al., 2013)
- Driving behaviour studies (Ning et al., 2013)
- Quality evaluation of highways (Li and Yang, 2013)
- Measurement of the effectiveness of traffic management measures (Minhans, 2013)

A literature review conducted by Austroads Incorporation (Austroads, 2006) on different multi-objective analysis techniques suggested that AHP was the most suitable option for highways asset owners to assist with optimising budget expenditure on maintenance schemes based on different criteria which should be considered for evaluating the condition of their assets. This is because, as highlighted in the aforementioned source, AHP is easy to use and provides a transparent and structured approach to problem decomposition, synthesis and option ranking through pairwise comparisons.

For complementing the optimisation model of the present study, AHP can be used by network planners in order to select suitable weighting factors which are embedded in the objective functions of the optimisation model (section 5.1.2 and 5.2.5). This, for instance, includes the weighting factors representing the importance of the two different types of disruption which were identified in this thesis (i.e. connectivity degradation of origin-destinations, and accessibility degradation of the links of the network). Furthermore, AHP can assist with finding suitable coefficients to weight the primary objective function of the optimisation model against the secondary objective function within the structure of the weighted sum method. Application of the AHP method, in the first place, requires a decision maker to set a number of *criteria* for scoring several *options* within the AHP model, and consequently choose a single option which achieves the highest score at the end.

An example for the application of AHP to deduce the weighting factors mentioned above is not provided in this thesis. However once the underlying criteria are defined, this will be a very straightforward exercise (e.g. see the detailed example provided in the aforementioned Austroads publication, 2006).

7.3.2. Application of multi-objective genetic algorithms

Multi-objective genetic algorithms have been developed by extending single-objective genetic algorithms in order to find the set of Pareto optimum points for a multi-objective optimisation problem. This is achieved mainly by modifying the embedded selection process of the genes and the way they are evaluated by the fitness function against all of the objective functions of the problem.

Multi-objective genetic algorithms retain all of the benefits they have for single-objective optimisation problems (as reviewed in section 7.2). They also have another appealing property which is their ability to converge to the Pareto optimal set – rather than a single Pareto optimum point – for multi-objective optimisation problems (Osyczka, 2002).

MATLAB provides a multi-objective genetic algorithm optimisation function which works very similarly to its single-objective version. However the selection process of the chromosomes is different in the way that to select new chromosomes for the next generation, all of the chromosomes in the present generation are scored against three criteria:

- The fitness value of a chromosome relating to the objective functions; this would result in an initial ranking of the chromosomes
- How far an individual is from the other individuals with the same rank
- The ability to increase the diversity of the population

The output of the multi-objective genetic algorithm is a set of Pareto optimal points for the optimisation problem, and is graphically represented by a *Pareto front diagram.*

7.4. The embedded steps in the proposed optimisation algorithm

The following steps, adopted from Yin (2000), illustrate each stage of the genetic algorithm which has been developed to solve the optimisation problem of this study.

Step 0: Code the decision variable *u* of the upper-level problem to a finite string y_i (the structure of y_i is described in section 7.5); determine the transform function to map the objective function of the upper-level problems to a fitness function.

Step 1: Using the creation function (see section 7.7), or at random if no such function is provided, select the initial population Y(*1*). Set k=1

Step 2: Calculate the fitness function (described in section 7.11) for individuals $y_j(k)\ k = 1,2,\dots,N$ by solving the lower-level optimisation problem, i.e. user equilibrium assignment, and reproduce the population Y(*k*) according to the distribution of the fitness function values

Step 3: Carry out the crossover and mutation operations (described in sections 7.9 and 7.10). Then a new population **Y**(*k* + 1) will be generated.

Step 4: If *k* = maximal number of generation, or another stop condition is met, adopt the individual with the highest fitness as the optimal solution of the problem. Else, set *k* = *k*+1 and return to Step 2.

7.5. Coding of the genetic algorithm individuals

An individual, associated with a candidate solution to the optimisation problem, is any point to which the fitness function can apply. The value of the fitness function for an individual is the score of that individual. An individual is sometimes referred to as a *genome;* and the vector entries of an individual are known as *genes* (e.g. the entries representing the start time of the schemes).

The structure of an individual to represent a scenario of street works schemes is illustrated on Figure 7-1.

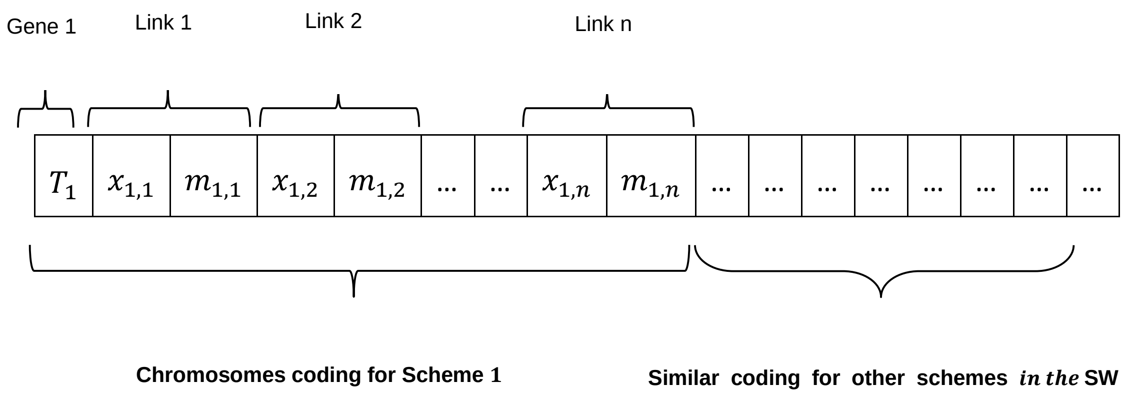


Figure 7-2 Structure of the candidate solution chromosomes

The following notations have been used:

$\boldsymbol{M_1}$: Set of the links subject to the scheme 1

$\boldsymbol{n}$: Number of the members of M_1

$\boldsymbol{SW}$: Set of street works schemes planned for the network

$\boldsymbol{T_1}$: Start time (day of the year) of scheme 1

$\boldsymbol{x_{1,1}}$: Position of link 1 in the sequence of the implementation of scheme 1

$\boldsymbol{m_{1,1}}$: Construction mode (also incorporating traffic management strategy) for link 1 during the implementation of scheme 1

An advantage of the above structure is that it can be easily expanded to incorporate new variables. For instance if $ns_{1,1}$ denotes 'working at night' (Boolean variable), and $d_{1,1}$ denotes 'the number of idling days for the construction crew during works', then the coding of the genes relating to link 1 subject to scheme 1 will be as follows (Figure 7-3).

$$\overbrace{\boxed{x_{1,1}}\boxed{m_{1,1}}\boxed{ns_{1,1}}\boxed{d_{1,1}}}^{\text{Link 1}}$$

Figure 7-3 Expanded structure of the genes (link 1 subject to scheme 1)

7.6. Addressing the integer nature of the optimisation problem

Most *selection*, *crossover* and *mutation* functions have been originally devised to perform for *continuous* type of numbers and fitness functions. For integer or mixed integer type of problems it would be necessary to use smart ways to make the genetic algorithm functions and procedures compatible with integer type of variables.

For the optimisation algorithm developed in this thesis, the following process has been devised to generate the random integer numbers which represent the sequence of the links that are subject to a given street works scheme (e.g. $x_{1,1}$ to $x_{1,n}$ on Figure 7-1):

Step 1: select five random numbers (of *real* type) in the range [0 6) to form the elements of a vector v_1 which will be passed to the fitness function. This is accomplished by defining *lower and upper bounds* (i.e. a bound vector) in MATLAB genetic algorithm '*options'* facility for the variables (genes) which represent the sequence of a link that is subject to a street works scheme.

Step 2: obtain the order of each number in the vector v_1 by using MATLAB *sort* function. The result is vector v_2 which contains corresponding integer values.

Step 3: elements of v_2 are associated to the relevant genes, i.e. x_1 to x_n , to represent the sequence of the links subject to a given street works scheme.

Similarly, the optimisation algorithm maps the random *real* type numbers resulting from different genetic algorithm procedures (e.g. selection, crossover and mutation) to suitable integer numbers. For instance given that three types of construction modes (corresponding to modes 0, 1 and 2) are available for a scheme, then the bound vector for the relevant variable is set to [0 3). Once a real random number is generated within the bound limits, then MATLAB *roof* function is utilised to choose the nearest integer value to this randomly selected real number. Similar to the random number of *real* type which is generated from a discrete uniform distribution, the resulting integer number is also obtained from the same distribution. This ensures that all integer modes have equal chances for selection by the genetic algorithm operators.

7.7. Selection of the initial population

By default, the initial population is selected on a random basis by the genetic algorithm function, and is subsequently passed to the fitness function for evaluation. However the number of generations required to reach the optimum or near optimum solutions can be reduced significantly if the approximate location of the solution values are known, and are passed to the optimisation function before a run starts.

Unless justified by issues such as coincidence with peak traffic times or special events in the network, the actual start time, sequence and traffic management option of the schemes are usually set to those best suitable for the schemes undertakers. Bearing this in mind, the process shown on Figure 7-4.**Error! Reference source not found.** has been devised to select the initial opulation for the optimisation algorithm.

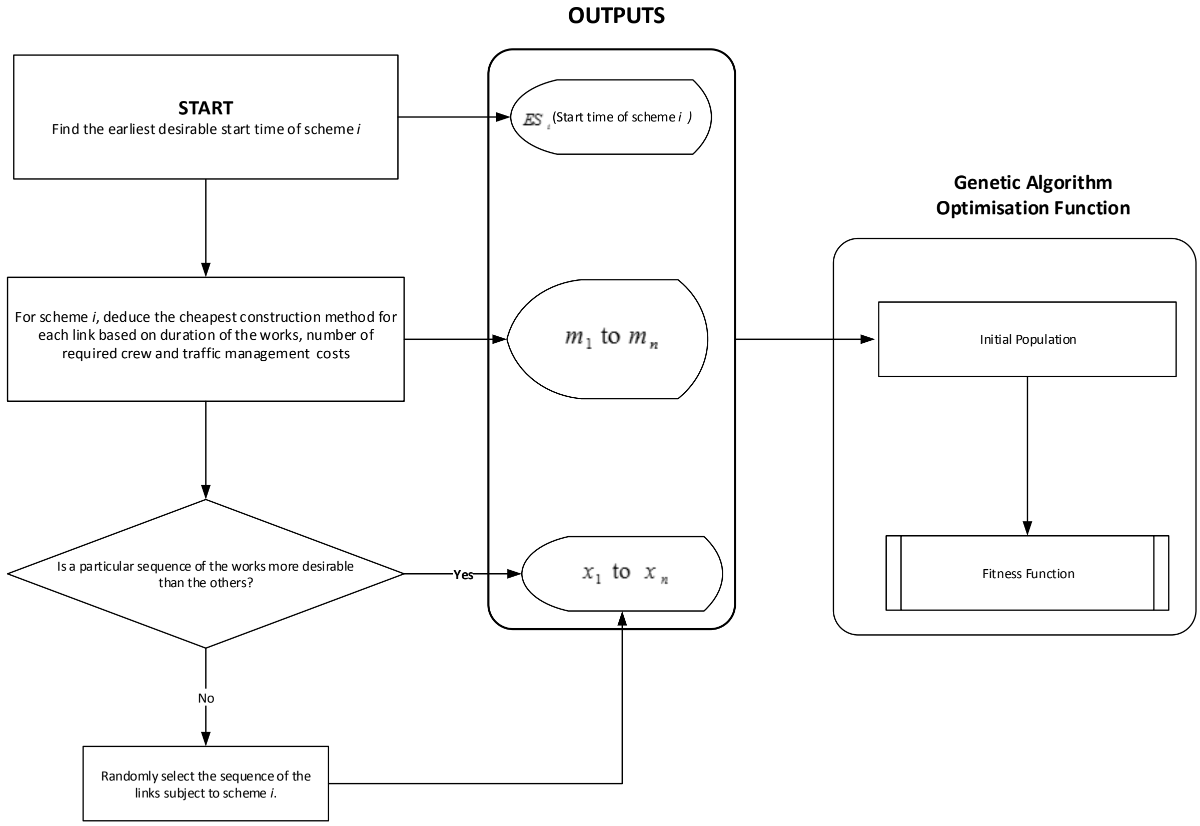


Figure 7-4 Process for selection of the initial population by the genetic algorithm function (to be repeated for schemes i = 1 to N)

However in order to validate the performance of an optimisation algorithm, the initial values of the optimisation variables may be deliberately selected from a region of undesirable points, to make finding the optimum solutions harder for the optimisation algorithm. This approach has been adopted in this thesis for a number of the experimental tests in chapter 8.

7.8. Providing bespoke arrangements in the optimisation model to encourage selection of more desirable scenarios

In order to reduce the adverse effects of street works, special arrangements may be made by a planner to combine all or some parts of two or more street works schemes. For instance two street works schemes may be undertaken at the same time on some links of a network, thus saving in traffic delay costs, and traffic management and construction costs. In such circumstances, it would be sensible to modify the optimisation function so that the scenarios with such preferred properties can get a higher chance of being generated by the optimisation algorithm during the random process of selecting candidate solutions.

Suppose that two street works schemes (e.g. scheme 1 and 2, referred to as *compatible schemes*) can be undertaken on a particular link of a traffic network simultaneously. This can be accommodated by adding a new *construction mode* for those links which are associated with the joint-working pattern that is available for schemes 1 and 2. As a result, the compatible schemes can be undertaken in one of the following three modes: mode 1 representing '*full link closure'*, mode 2 representing '*half link closure'* and mode 3 representing *'full link closure and simultaneous works on both schemes'.* Now in order to increase the chance of mode 3 being selected by the optimisation algorithm for both of the compatible schemes for a given link, the genetic algorithm function is modified to choose mode 3 for both schemes even if mode 3 had been originally generated for only one of the schemes. Given that mode 3 is selected for one scheme in this way, the start time of one of the schemes should be amended in a way that both schemes are carried out at the same time for the link under question.

It is unlikely that one particular set of procedures would suit all types of the *desirable scenarios* which need to be encouraged during the selection process of the optimisation algorithm. However all such procedures involve making some sort of smart modifications to the optimisation algorithm processes in order to increase the chance of the more desirable scenarios being created during the generation of new individuals.

In order to secure the ability of the optimisation algorithm to assess all potential solutions, it is important to ensure that no feasible scenario is completely ruled out. For example for the aforementioned case of two compatible schemes with a joint-working option, this means that the optimisation algorithm should still allow compatible schemes to be undertaken by mode 1 or mode 2 on a given link (i.e. non-simultaneous working). This can be accommodated by incorporating one or several *auxiliary genes* (i.e. variables) into the structure of a candidate solution chromosomes. Each auxiliary variable, of Boolean type, will be associated to a particular type of pre-planned desirable scenario. If the given auxiliary variable returns 1, the optimisation algorithm amends some other genes to generate a pre-determined desirable scenario before being evaluated by the fitness function. Otherwise the original genes would be passed to the fitness function unchanged. Examples of such desirable scenarios include: undertaking two schemes at the same time on some links, or choosing a particular sequence of link closures for a scheme (due to, for instance, operational requirements).

7.9. Crossover operation

The crossover operation specifies how the genetic algorithm combines two individuals, or parents, to form a crossover child for the next generation.

There is a variety of functions which have been developed for the crossover operation in the literature (e.g. see MathWorks Inc., 2014b; and Poli et al., 2008) such as *single-point, two-point, intermediate, heuristic*, and *arithmetic crossover functions*. However the most common option appears to be the *scattered crossover function* whereby a random binary vector is created, and genes are selected from the first parent where the vector is a 1, and from the second parent where the vector is a 0. This is illustrated by the example shown on Figure 7-5 for a binary vector of [1 1 0 0 1 0]

$\boldsymbol{Parent_1} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{x_3}\ \boldsymbol{x_4}\ \boldsymbol{x_5}\ \boldsymbol{x_6}]$ & $\boldsymbol{Parent_2} = [\boldsymbol{y_1}\ \boldsymbol{y_2}\ \boldsymbol{y_3}\ \boldsymbol{x_4}\ \boldsymbol{x_5}\ \boldsymbol{x_6}]$

then:

$\boldsymbol{Child_1} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{y_3}\ \boldsymbol{y_4}\ \boldsymbol{x_5}\ \boldsymbol{y_6}]$

Figure 7-5 An example for the scattered crossover function

The optimisation algorithm of this study incorporates the scattered crossover function which is also supported by MATLAB genetic algorithm functions.

7.10. Mutation operation

The mutation operation specifies how the genetic algorithm makes small random changes in the individuals of a population to create mutation children. Mutation is thus intended to provide diversity and enable the genetic algorithm to search a broader space.

$\boldsymbol{Parent} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{x_3}\ \boldsymbol{x_4}\ \boldsymbol{x_5}\ \boldsymbol{x_6} \ldots]$ then:

$\boldsymbol{Child} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{y_3}\ \boldsymbol{y_4}\ \boldsymbol{x_5}\ \boldsymbol{y_6} \ldots]$

Figure 7-6 Illustration of a mutation function

The *Gaussian function* available in MATLAB is a well-known mutation function which has been selected for the optimisation algorithm of this study (several alternatives such as the *uniform* and the *adaptive feasible* mutation functions are available too). The Gaussian adds a random number taken from a Gaussian distribution with mean 0 to each entry of the parent vector.

The standard deviation (σ_k) of this distribution is determined by two parameters with the following equation:

$\sigma_k = \sigma_{k-1} \left(1 - Shrink \frac{k}{Generations}\right)$ (Eq 7.3)

- *Scale:* the standard deviation at the first generation (σ_1); and:
- *Shrink*: controlling how the standard deviation shrinks as the generations go by

k = Generation number

The default value of both Scale and Shrink is 1 in MATLAB, which are maintained for the optimisation algorithm of this study.

7.11. Fitness function of the optimisation algorithm

Devising the fitness function is one of the most onerous parts of the development of a genetic algorithm. One reason is that the fitness function must usually fulfil several tasks before generating a final score for the candidate solutions at each generation.

The main task of the fitness function is scoring the candidate solutions which are generated by the genetic algorithm function at each generation. Using the two objective functions of the optimisation problem, this is achieved by calculating the total costs and disruptive effects of street works schemes.

The fitness function also has the role of ensuring that the population individuals satisfy the constraints which have been defined by the programme (see section 7.12). Furthermore, the fitness function must ensure that the children whose properties are generated from the parents by the crossover and mutation operators remain feasible solutions before their scores are evaluated by the optimisation algorithm. For instance an infeasible solution candidate could arise if the construction mode which is created by the crossover or mutation operation would be inconsistent with the link under question. If such a condition arises, the fitness function would take appropriate corrective measure by changing the inconsistent value of that given variable to a suitable value.

The way the individuals have been coded in this model, and the bounds set for each variable, should ensure that the vast majority of the children, if not all, remain feasible individuals to be scored by the fitness function. This has been achieved by defining the structure of the chromosomes *smartly*, for instance in the way that ‘the sequence of a link’ is taken as a variable (gene) in the structure of a chromosome, rather than taking the index of the link which is subject to each stage of the works.

7.12. Dealing with constraints in the optimisation algorithm

Various hard or soft constraints may be set for the street works schemes which are planned in a traffic network, such as: their earliest start dates, the latest completion dates, restriction on the duration of the schemes, the diversion routes used for the restricted traffic, and so on.

MATLAB genetic algorithm function guarantees to create the population of individuals that are generated by its procedures in such a way that the linear constraints and bounds are never violated (MathWorks Inc., 2014b). However a conflict between two street works schemes may still happen as a result of some combination of the values of the genes pertaining to different schemes. The most significant example is the conflict between two *incompatible* schemes to be implemented at the same time on a given link. These circumstances are not known until the start time and duration of the schemes on each link are calculated by the fitness function.

A review by Coello and Artemio (2012) reveals that the *penalty function method* (Fiacco and McCormick, 1968), and the *stochastic ranking method* (Runarsson and Yao, 2000) are the two most common alternative approaches to deal with this type of constraint optimisation problem (Runarsson and Yao, 2000):

The penalty function approach entails introducing a *penalty term* into the objective function in order to penalise constraint violations. Runarsson and Yao (2000) noted that the penalty function method has been very common and may work quite well for some problems. However, deciding an optimal (or near-optimal) value for the penalty term can be difficult: If it is too small, an infeasible solution may not be penalised enough. Hence, an infeasible solution may be evolved by an evolutionary algorithm such as the genetic algorithms. If it is too large, a feasible solution is very likely to be found, but could be of very poor quality. For these reasons, they introduced a new approach which allows the objective and penalty functions to be balanced stochastically. This is referred to as the *stochastic ranking method*.

The optimisation algorithm devised in this study uses the penalty function method which is more common and straightforward than the stochastic ranking method. The penalty function method is also more suitable to illustrate, for validation purposes, how the optimisation algorithm progresses from the space of infeasible candidates towards the feasible solutions. Nonetheless the potential merits of the stochastic ranking method for application to the optimisation algorithm of this study has been identified as an area for future work in chapter 9.

7.13. Chapter concluding remarks

First in this chapter, a formula was developed to count the number of scenarios which are theoretically feasible in a traffic network for a set of street works schemes. This formula showed that the number of feasible options for realistic size networks would be extremely high, thus highlighting the need for an optimisation algorithm to find the optimum or near optimum scenarios.

Next, genetic algorithms optimisation methodology was selected for application to the optimisation problem of this study. This was due to the nature of the optimisation problem, and considering a range of desirable characteristics observed in genetic algorithms. To code the optimisation algorithm, the genetic algorithm *function* available in MATLAB package was selected.

Different procedures and elements of the proposed optimisation algorithm were described in this chapter. In particular, coding the structure of genetic algorithm chromosomes, the crossover and mutation operators, and the fitness function of the optimisation algorithm were covered in this chapter. These components had to be developed or selected robustly and appropriately in order to suit the optimisation problem of this study.

The optimisation algorithm devised here is to be verified by undertaking a number of experimental tests in the next chapter of this thesis.

Chapter 8
Verifying the Performance of the Optimisation Model (Experimental Tests)

In this chapter the results of a number of experimental tests for planning several street works schemes in a network are presented, in order to evaluate the performance of the optimisation model. Initially the optimisation model is applied to a small hypothetical network for three street works schemes to minimise the primary objective function of the model. Subsequently the same network is used for minimising both of the objective functions for the same number of street works schemes. Finally the applicability of the optimisation model to real size traffic networks is discussed.

Using a small hypothetical network allows the interaction between the optimisation variables and the objective functions of the model, as well as the prevailing trade-offs among them, to be more clearly visible from the optimisation results. This would not be possible using larger networks due to the complexities arising from the increase in the number of optimisation variables.

8.1. Experiment 1: Single objective optimisation

8.1.1. Description of the network and origin-destination journeys

A very simple and small hypothetical network, borrowed from the paper by Ballijepalli et al. (2004), is selected for undertaking the tests of this chapter. This is shown on Figure 8-1. The network consists of four nodes, five links and two origin-destination pairs which are denoted by ‘A’ to ‘C’ and ‘B’ to ‘C’.

Travel time functions of all links are expressed by the well-known US Bureau of Public Roads (1964) function, as introduced earlier in section 6.6, in the form of $c_i = a_i + b_i(\frac{f}{40})^4$.

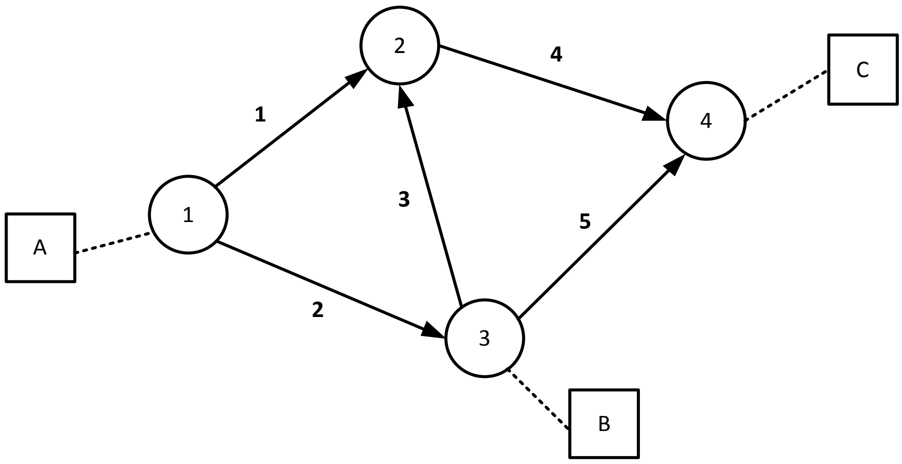


Figure 8-1 five-link network with five paths and two origin-destination pairs

c_i is the travel time for link i based on the flow passing that link (f_i) which is measured in ‘passenger car unit’ per hour (pcu/hour). a_i and b_i are parameters with fixed values for a given condition (mode) of a link. It is assumed that the base origin-destination flows are 200 pcu/hr for ‘A’ to ‘C’ and 100 pcu/hr for ‘B’ to ‘C’ movements. These are taken as average hourly traffic volumes per a shift of work. Each shift of work is assumed to be 7 hours long.

Three modes are defined for each link denoted by mode 0, mode 1 and mode 2 which are associated with a given link to be fully closed, half closed and completely open. The value of the coefficients a and b are shown in the following table.

Table 8-1 Link travel time function parameters for experimental tests

Parameters	**Mode**	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Link 5**
a	Modes 1 & 2	6	4	2	3	5
b	Mode 1	1.81	1.21	0.62	0.90	1.50
	Mode 2	0.90	0.60	0.30	0.45	0.75

Paths (routes) travel times for un-degraded network condition have been calculated for the base origin-destination volumes in accordance with Wardrop user equilibrium condition and are shown in Table 8-2:

Table 8-2 Path flows and travel times for experiment 1 tests.

OD No	Path No	Path	Flow(pcu/hr)	Travel time (hr)
1	1	A→link1→link4→C	95.1	151.5
	2	A→link2→link5→C	73.1	151.5
	3	A→link2→link3→link4→C	31.8	151.5
2	4	B→link5→C	67.4	119.2
	5	B→link3→link4→C	32.6	119.2

All schemes are required to be completed within the planning period which is set to be 120 (working) days.

Network traffic volumes during the planning period are shown on Figure 8-2 as a coefficient of the base origin-destination flows (note different traffic volumes, shown in red lines, for OD1 and OD2 between day 0 and day 10)

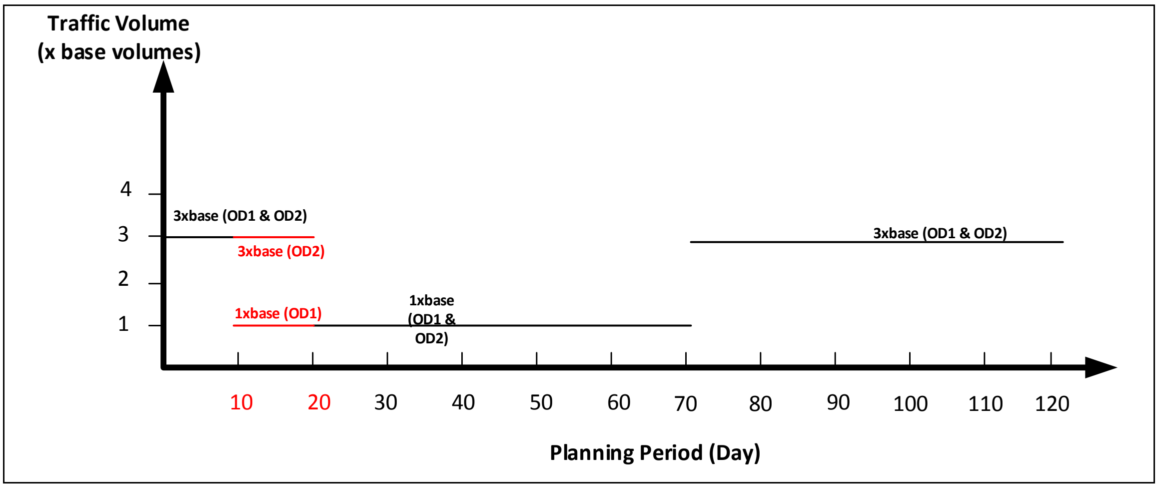


Figure 8-2 Origin destination volumes

8.1.2. Description of the street works schemes

Three hypothetical street works schemes are considered for implementation in this network. The durations of the schemes on each link, which would be dependent on the mode of an affected link during the street works activities, are shown in Table 8-3. Only links 1 to 4 are subject to the schemes.

Table 8-3 Duration of street works (in number of shifts) for experiment 1 tests

	Scheme 1		Scheme 2		Scheme 3	
Mode No →	0	1	0	1	0	1
Link 1	2	3	2	4	5	9
Link 2	2	3	2	4	5	9
Link 3	2	3	2	4	5	9
Link 4	2	3	2	4	5	9

The cost of undertaking the works (including traffic management costs) for each link is provided in Table 8-4. It is assumed that, for scheme 1, undertaking the required works on link 1 and 2 would be practically unfeasible unless a full closure traffic management (i.e. mode 0) can be provided. Therefore a relatively large figure (i.e. £90,000) have been specified in this table in the cells relating to mode 1.

Table 8-4 Cost (£) of street works schemes for experiment 1 tests

	Scheme 1		Scheme 2		Scheme 3	
Mode No →	0	1	0	1	0	1
Link 1	4,000	90,000	3,000	2,000	5,000	4,000
Link 2	4,000	90,000	3,000	2,000	5,000	4,000
Link 3	4,000	90,000	3,000	2,000	5,000	4,000
Link 4	4,000	90,000	3,000	2,000	5,000	4,000

A fixed daily cost is attributed to the delay in completion of each scheme in order to encourage the works to be completed as soon as possible. This is taken as £1,000, £8,000 and £40,000 a day for schemes 1 to 3 respectively. Therefore scheme 3 is expected to be prioritised over scheme 2, and scheme 2 over scheme 1, should a conflict arise. It is also assumed that for practical reasons, link 1 should always precede link 4 when they are subject to scheme 1 and scheme 2 (this restriction is introduced to the optimisation algorithm by applying a penalty function to any scenarios violating this condition).

All schemes are assumed to be incompatible, i.e. no two schemes can be undertaken at the same time on one link. This is because

The travellers on the partially degraded paths are assumed not to change their routes, and those on closed paths are presumed to be using pre-defined diversion routes. This is based on the simple assumption that travellers remain unaware of the street works degrading link capacities until they face completely closed links during their journeys, at which points they would use predefined diversion routes to continue their journeys (Table 8-5 includes the diversion routes considered for each path).

The assumption described above is associated with a *non-elastic or fixed* travel demand situation (see section 3.1.1). For this exercise, all scenarios which involve the blockage of an origin-destination movement of the network are treated as *infeasible scenarios* by the fitness function of the optimisation algorithm. When an infeasible scenario is generated during an optimisation run, it will result in a penalty value (see section 7.12) being applied to the fitness function upon evaluating that scenario. Therefore on the diagrams (e.g. Figure 8-3) which illustrate the progress of an optimisation run, infeasible scenarios will be represented by those points which have extremely high fitness values.

Table 8-5 Diversion routes

Path No	Diversion
1	2, and 3 (if 2 is closed)
2	1, and 3 (if 1 is closed)
3	1, and 2 (if 1 is closed)
4	5
5	4

8.1.3. Experiment 1 test results

The optimisation model was performed on a computer with Intel Core i5 Processor (2.5GHz) with 6Gb of RAM. The optimisation model was tasked to find optimum values for the resulting 27 variables (introduced later in this section) which have been numbered in table 8-6.

The optimisation function is set to stop if one of the stopping conditions are met: This mainly includes the predefined number of generations which is set to 100 for this test, and default limit on *stall generations* which is related to the weighted average change in the fitness function value. The algorithm stops if the stall generation value is less than a predefined tolerance value (set to 1e-6 by default).

A genetic algorithm is a stochastic process, that is, it makes many random choices during an optimisation run, and thus different results are produced each time an optimisation run is completed. For this reason and in order to check the reliability of the model, the genetic algorithm is repeated 10 times for the same test in order to compare the results.

The progress of the optimisation algorithm for one of the runs is shown on Figure 8-3. The black points denote the best fitness value at each generation of the population (a generation consists of 50 chromosomes), and the blue points denote the average value of the fitness function for a generation.

On Figure 8-3, the points which represent relatively very high values of the fitness function are observed from generation 1 to approximately generation 18. These points represent the *unfeasible solutions*, and therefore have incurred a predefined penalty value by the fitness function of the optimisation algorithm. Conversely all scenarios generated from generation 18 onwards represent feasible solutions on this figure.

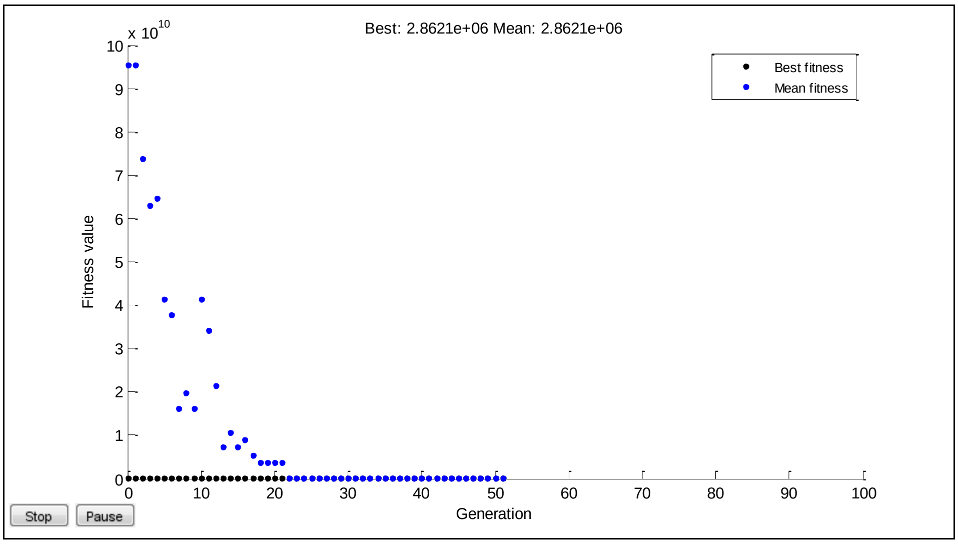


Figure 8-3 Progress of the optimisation model (test 1-1)

Table 8-6, Table 8-7 and Figure 8-4 contain the result of ten run of the optimisation model: This includes the values relating to the start times of the schemes (S_i), positions of the links ($L_{i,1}$ to $L_{i,4}$) in the sequence of the works for each scheme, and the modes of the schemes during the street works activities ($M_{i,1}$ to $M_{i,4}$), where *i* (=1 to 3) is the index of each scheme. It may be recalled that all schemes are implemented on links 1 to 4, and link 5 always remains unaffected – in terms of its capacity – during the implementation of the schemes.

As expected scheme 1 and scheme 2 have completed during the off-peak period for both Origin-Destinations (ODs) which starts from day 20 to day 70, since they have relatively low daily costs (£1000 and £8000 respectively) for delay in completion of the schemes. Scheme 1 starts later than scheme 2 in 8 out of 10 runs as it has a lower daily cost for delay in completion.

Scheme 3, however, has quite a high figure for each day of delay in completion. The results show that it starts shortly after the peak traffic period for both ODs (i.e. between day 1 and day 10). Between day 10 and day 20 (as shown on Figure 8-2) only OD2 has peak traffic volumes which mainly affect link 3, 4 and 5. Therefore for scheme 3, works on link 1 and 2 start before works on link 3 and 4. In Table 8-2, this is manifested by the $L_{3,1}$ and $L_{3,2}$ being always lower than $L_{3,3}$ and $L_{3,4}$.

The restrictions introduced in section 8.1.2 in relation to the sequence of the works for scheme 1 and 2 have resulted in the stage numbers for link 1 being always lower than those for link 4 (i.e. $L_{1,1}$ and $L_{2,1}$ are lower than $L_{1,4}$ and $L_{2,4}$ respectively).

As expected, scheme 1 has operated by mode 0 for all links as otherwise the construction costs would have been too high (based on the relevant figures in Table 8-4). For scheme 2 and 3, however, the outputs show varying results for link modes. This is because on one hand the total construction cost of schemes would be lower with full closure traffic managements (mode 0) based on the input figures provided in Table 8-4. On the other hand, however, in some scenarios full link closure arrangements can result in significantly high cost of delays to the diverted traffic, as well as travellers on the links accepting the diverted traffic.

Table 8-6 Fitness function values of the experiment 1 tests

Run No	1	2	3	4	5	6	7	8	9	10
Fitness Function Value (£)	2,862,100	2,773,600	2,737,200	2,642,200	2,664,100	2,797,000	2,657,800	2,620,900	2,724,100	2,693,100

Table 8-7 Optimisation results of the experiment 1 tests

(The initial values set for the model are shown in red colour).

Run No	Start Time	Stage No				Mode No			
	S_1	$L_{1,1}$	$L_{1,2}$	$L_{1,3}$	$L_{1,4}$	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$
	5	2	3	1	4	1	1	1	1
1	35	1	3	4	2	0	0	0	0
2	40	1	3	2	4	0	0	0	0
3	21	1	4	3	2	0	0	0	0
4	31	3	1	2	4	0	0	0	0
5	49	1	3	4	2	0	0	0	0
6	45	2	4	1	3	0	0	0	0
7	32	1	3	2	4	0	0	0	0
8	27	1	3	4	2	0	0	0	0
9	57	2	4	1	3	0	0	0	0
10	41	3	1	2	4	0	0	0	0
	S_2	$L_{2,1}$	$L_{2,2}$	$L_{2,3}$	$L_{2,4}$	$M_{2,1}$	$M_{2,2}$	$M_{2,3}$	$M_{2,4}$
	10	4	1	2	3	1	1	1	1
1	31	2	1	4	3	0	0	0	0
2	32	1	4	2	3	1	1	0	1
3	33	1	4	3	2	1	1	0	1
4	27	1	2	4	3	1	0	0	1
5	17	2	1	3	4	1	1	0	1
6	28	1	4	2	3	1	0	0	1
7	25	1	4	2	3	1	0	0	1
8	29	1	4	2	3	0	1	0	1
9	23	3	1	2	4	1	1	0	1
10	21	3	1	2	4	1	0	0	1
	S_3	$L_{3,1}$	$L_{3,2}$	$L_{3,3}$	$L_{3,4}$	$M_{3,1}$	$M_{3,2}$	$M_{3,3}$	$M_{3,4}$
	15	2	3	4	1	1	1	1	1
1	14	2	1	3	4	1	0	0	0
2	11	2	1	3	4	1	1	0	1
3	11	2	1	3	4	1	0	0	1
4	11	2	1	3	4	1	1	0	1
5	11	2	1	4	3	1	0	0	1
6	11	2	1	4	3	1	1	0	1
7	11	2	1	4	3	1	0	0	1
8	12	2	1	4	3	1	0	0	0
9	11	2	1	3	4	1	0	0	1
10	11	1	2	4	3	1	0	0	1

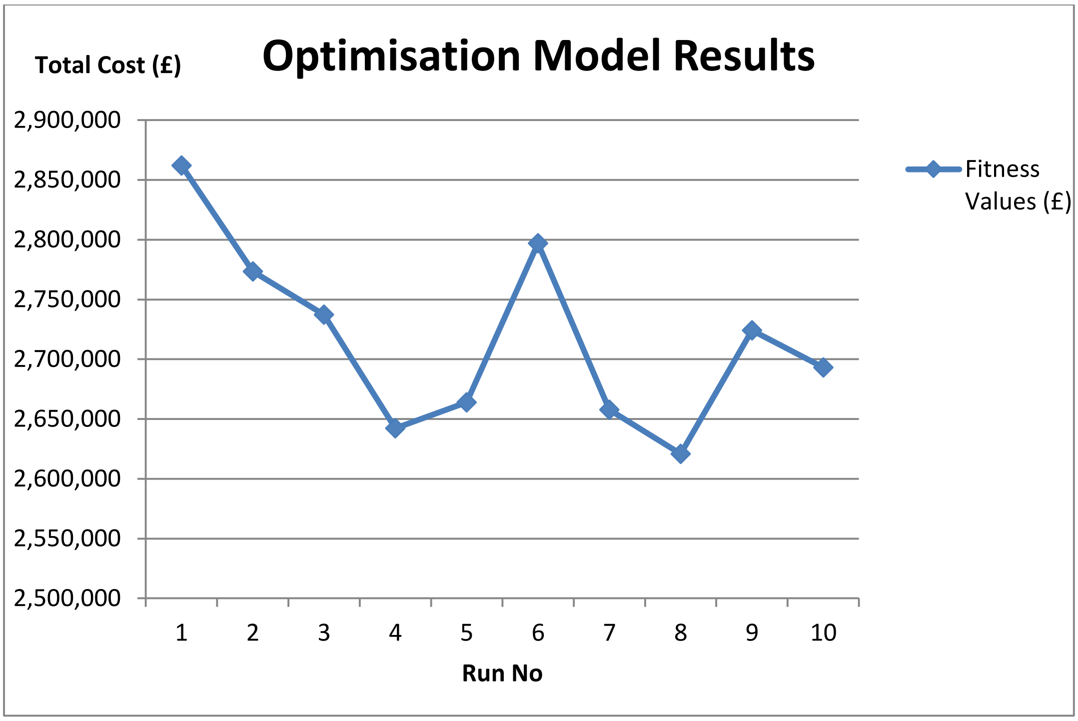


Figure 8-4 Fitness values associated with 10 runs of the optimisation model (experiment 1 tests)

The average of the fitness function values obtained for 10 runs is £2,692,050. However the minimum value of the fitness function was obtained from Run 8 as £2,620,900.

The *relative standard deviation* - i.e. the absolute value of the *coefficient of variation* (CV) - of the 10 results has worked out as 2.2% which is quite low. However this still indicates that each run of the optimisation model can only warrant a near optimum solution. Since all runs have shown to be terminated well before reaching the maximum number of generations (100), the performance of the optimisation model is likely to be improved by modifying a number of underlying parameters of the crossover and mutation functions (see section 7.9 and 7.10). Such modifications may lead to increasing the diversity of the populations which are evaluated by the genetic algorithm model, therefore enhancing the resulting solutions.

8.2. Experiment 2: multi-objective optimisation

In section 8.1, the performance of the optimisation algorithm for minimising the primary objective function of the optimisation problem was tested. The tests conducted in this section, collectively referred to as experiment 2 tests, are intended to evaluate the performance of the optimisation algorithm for minimising both of the objectives which were identified in Chapter 5. In particular, these tests can illustrate the difference which is made to the optimum results due to the incorporation of the secondary objective function which is tasked to measure the non-monetised disruptive effects of street works in a network.

Before conducting multi-objective optimisation tests in sections 8.2.3 and 8.2.4, it was deemed necessary to validate the performance of the optimisation model for each objective function separately. This validation was previously undertaken for the primary objective function in section 8.1, and is conducted for the secondary objective function in section 8.2.2.

8.2.1. Description of the assumptions

The same network and origin-destination traffic movements which were introduced in section 8.1 for experiment 1 tests have been used for the tests that are conducted in section 8.2. This also includes the same link travel time functions, coefficients and the diversion routes which were specified in section 8.1. Cost of street works schemes are provided in Table 8-8.

Table 8-8 Cost (£) of street works schemes for experiment 2 tests

	Scheme 1		Scheme 2		Scheme 3	
Mode No →	0	1	0	1	0	1
Link 1	4,000	3,000	3,000	2,000	5,000	4,000
Link 2	4,000	3,000	3,000	2,000	5,000	4,000
Link 3	4,000	3,000	3,000	2,000	5,000	4,000
Link 4	4,000	3,000	3,000	2,000	5,000	4,000

The fixed daily cost for the delay in completion of each scheme is taken as £1,000, £2,000 and £40,000 for schemes 1 to 3 respectively.

Traffic volumes for the origin destinations of the network are shown on Figure 8-5 in reference to the base values provided in section 8.1.1.

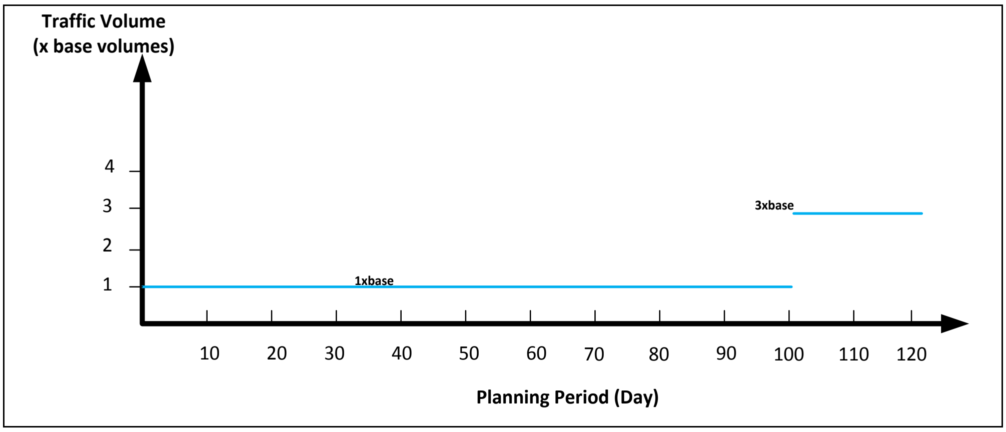


Figure 8-5 Origin-destination traffic volumes for experiment 2 tests

The steady traffic volumes assumed for the following tests are to ensure that the trade-off effects between other key parameters of the model, notably start time of the schemes and traffic management modes, are easily noticed in the test results. Based on the traffic volumes provided on this figure, no street works schemes resulting from running the optimisation algorithm are expected to coincide with the high-volume traffic period starting from day 100. This is due to the otherwise extremely high cost of delays which would be incurred by road travellers.

Figure 8-6 shows the variations of the time-sensitivity level which has been assumed for the planning horizon.

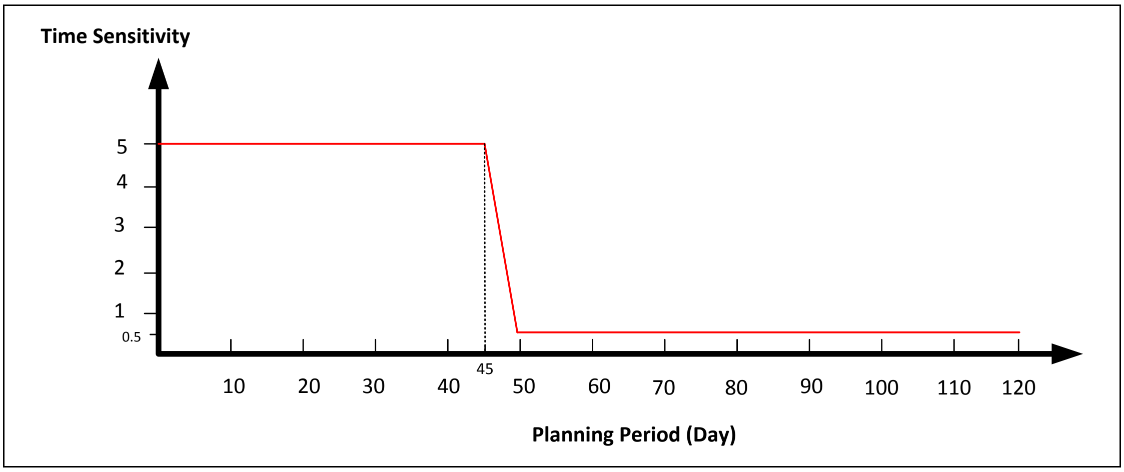


Figure 8-6 Time-sensitivity variations during the planning period for experiment 2 tests

This diagram indicates that the time-sensitivity during the planning period is set at the maximum 5.0 level until day 45. From this point, it drops sharply until day 50 to reach a low value of 0.5, and then remains constant at this value for the rest of the planning period.

The accessibility degradation scores of all links are assumed to equal 5.0 during full link closure (mode 0) periods, and 1.5 during partial link closure (mode 1) periods.

Degradation of the connectivity of origin-destinations of the network are measured based on the c_i coefficient which was first introduced in chapter 5 (section 5.2.3.1) for a given origin-destination, as follows:

$$c_i = \frac{Minimum\ OD\ travel\ cost\ under\ degraded\ conditions}{Minimum\ OD\ travel\ cost\ under\ un{-}degraded\ conditions}$$

Figure 8-7 shows the connectivity-degradation function which has been used for all origin-destinations of the network:

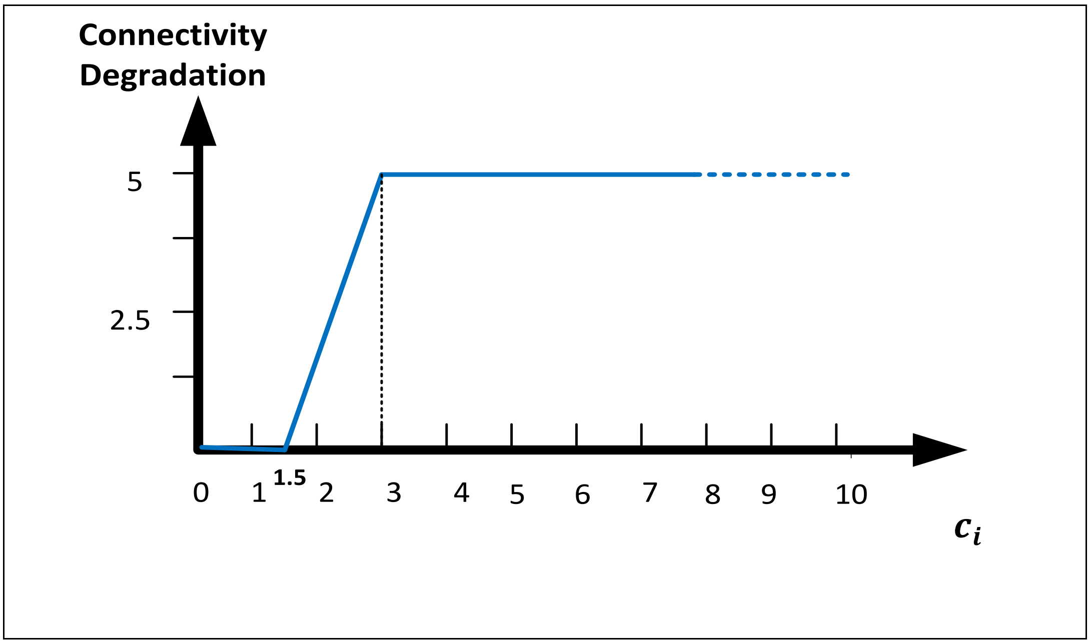


Figure 8-7 Connectivity degradation function of the origin-destination traffic movements (experiment 2 tests)

As shown on this figure, the connectivity degradation of a given origin-destination starts from the point associated with $c_i = 1.5$, and then linearly increases until $c_i = 3$. For fully blocked origin destinations or those associated with c_i values equal or higher than 3, the connectivity degradation level is 5 (i.e. maximum level of degradation).

Figure 8-8 shows the fuzzy membership functions which are used to associate the accessibility degradation levels of the network links (scalar values on the horizontal axis) to the fuzzy attributes of '*highly degraded'*, '*modestly degraded*' and '*slightly degraded'*. These fuzzy attributes are measured by membership degrees ranging from 0 to 1 on the vertical axis of the diagram.

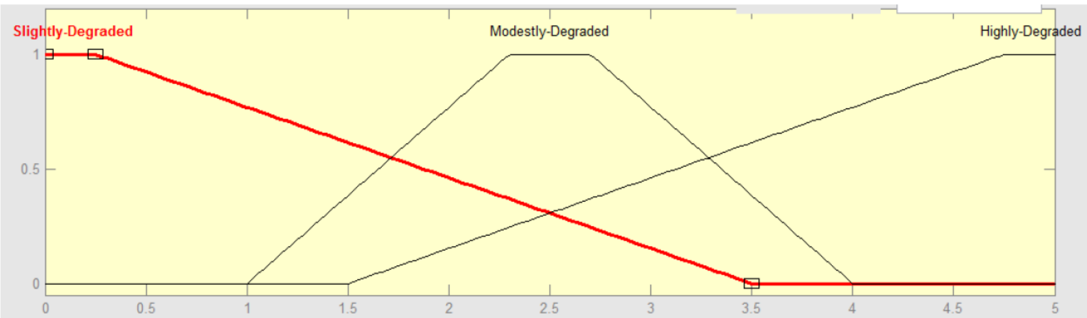


Figure 8-8 Fuzzy membership functions for link-related accessibility degradation (experiment 2 tests)

Fuzzy membership functions with similar shapes have been used for the other input attributes of the model, including the 'origin-destination degradation', 'time-sensitivity' and 'disruption'. These are shown on Figure 8-9 to Figure 8-10.

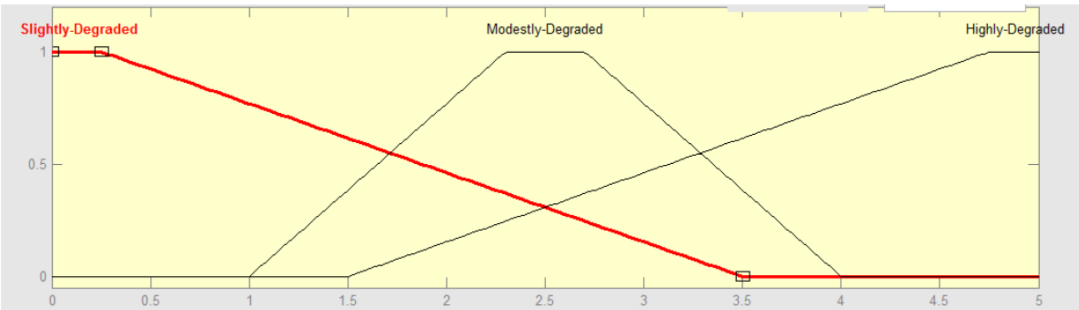


Figure 8-9 Fuzzy membership functions for origin-destination connectivity degradation (experiment 2 tests)

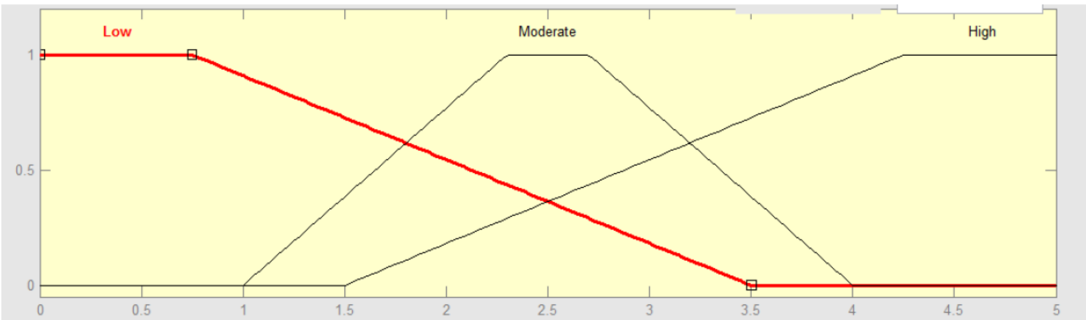


Figure 8-10 Fuzzy membership functions for 'time sensitivity' (experiment 2 tests)

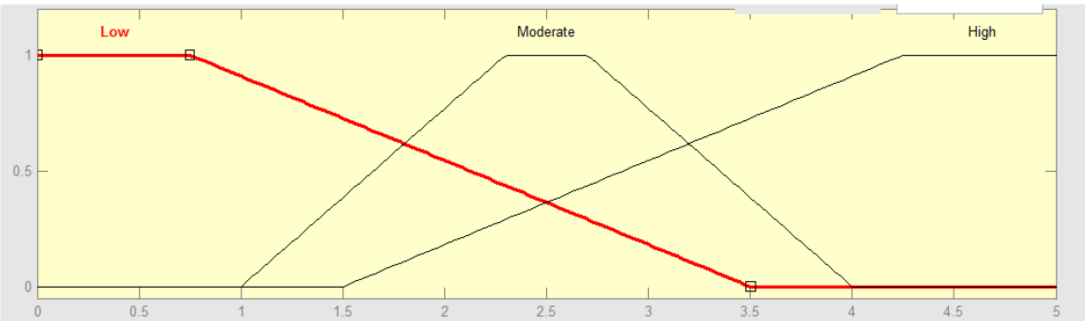


Figure 8-11 Fuzzy membership functions for 'disruption' (experiment 2 tests)

The fuzzy rules which have been used in order to infer accessibility related disruption to the network links are specified below:

1. If 'link accessibility is 'slightly degraded', 'disruption' is 'low'
2. If 'link accessibility' is 'modestly degraded' and 'time sensitivity' is 'moderate', 'disruption' is 'average'
3. If 'link accessibility is 'highly degraded' and 'time sensitivity' is 'high', 'disruption' is 'high'

Exactly the same rules have been used for the inference of the disruption which is caused due to the connectivity degradation of the origin-destinations.

The disruption scores of the links and origin-destinations of the network are scaled to fall within a 0 to 100 range:

Figure 8-12 shows how the disruption score for a link is inferred for one pair of input values: For link accessibility-degradation = 3.5 and time-sensitivity = 4, the resulting disruption score is 81.9.

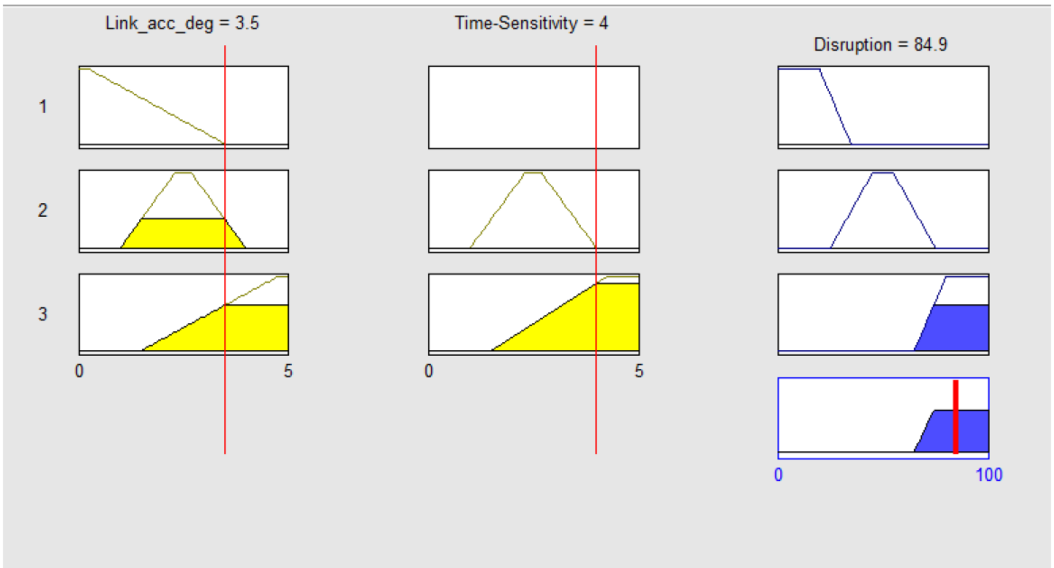


Figure 8-12 Example of the inference of the disruption score for a pair of input values

The fuzzy rules specified in this section have been devised in the way that they encourage those street works activities with low impact on link-related accessibility levels at **any time** (i.e. regardless of the time sensitivity of the network). On the other hand street works activities with high impact on link-related accessibility are only encouraged at **insensitive times**, as otherwise they will result in high disruption scores. This is evident on Figure 8-13 where two symmetric pairs ([1.5,5] & [5,1.5]) associated with 'link accessibility degradation' and 'time sensitivity' have led to different disruption scores of 15.1 for the first pair, and 50.0 for the second pair.

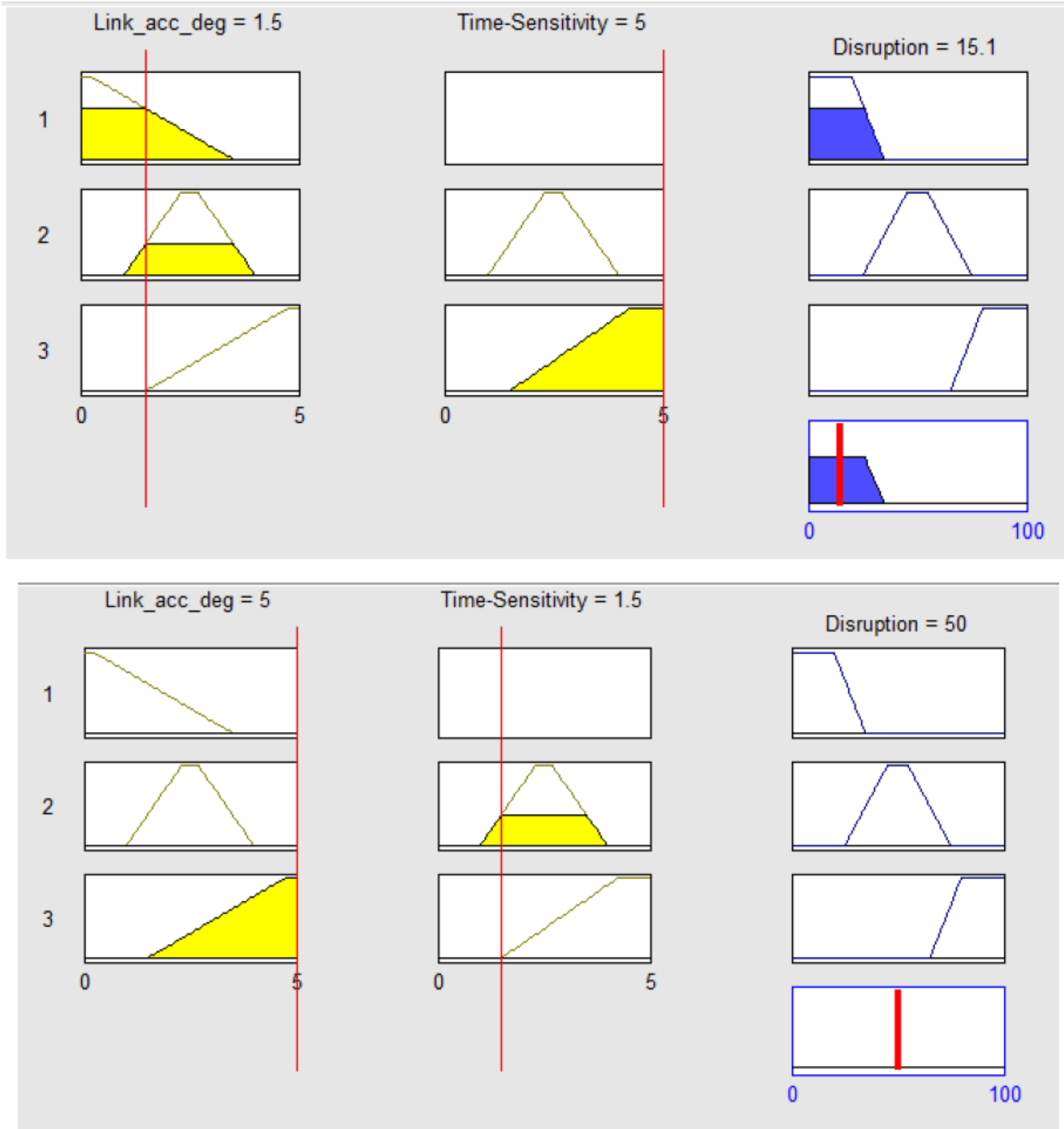


Figure 8-13 Comparison between the disruption score values resulting from two pairs of symmetric numbers

(The pairs are associated with 'link accessiblity degradation' and 'time sensitivity').

The total disruption of the network during a working shift consists of the weighted sum of the *link related* and *origin-destination related* disruptions. This experiment assumes a weighting factor of 3 has been set by the planners to reflect the relative importance of an origin-destination related disruption score over a link-related disruption score.

No restriction has been set for the maximum allowable level of delay costs or disruption levels during a working shift. Other specific assumptions for each test will be stated in the relevant sections.

8.2.2. Validation of the optimisation algorithm for the secondary objective function (test 2-1)

The secondary objective function of the optimisation model was introduced in Chapter 5, alongside the primary objective function, in order to measure the non-monetised disruptive effects of street works activities. In this section and before testing the optimisation model with both objectives, the performance of the optimisation algorithm to find the least disruptive street works scenarios is verified with one test. Similar to the experiment in section 8.1, this verification entails running the optimisation algorithm with a single objective function.

Duration of the works for all links is assumed to be four shifts regardless of the link modes. As this test is only concerned with evaluating street works scenarios against the secondary objective function, those parameters which only influence the primary objective function (e.g. cost of the works for each shift) will not impact on the results of the test.

The initial population which is set for the optimisation algorithm has been deliberately selected to initiate a highly disruptive scenario (shown in Table 8-9). This is as a result of the values selected for the start times of the schemes, and the modes of the links at the time the optimisation run starts .

The progress of the optimisation algorithm, taking about 150 seconds to complete, is illustrated on Figure 8-14.

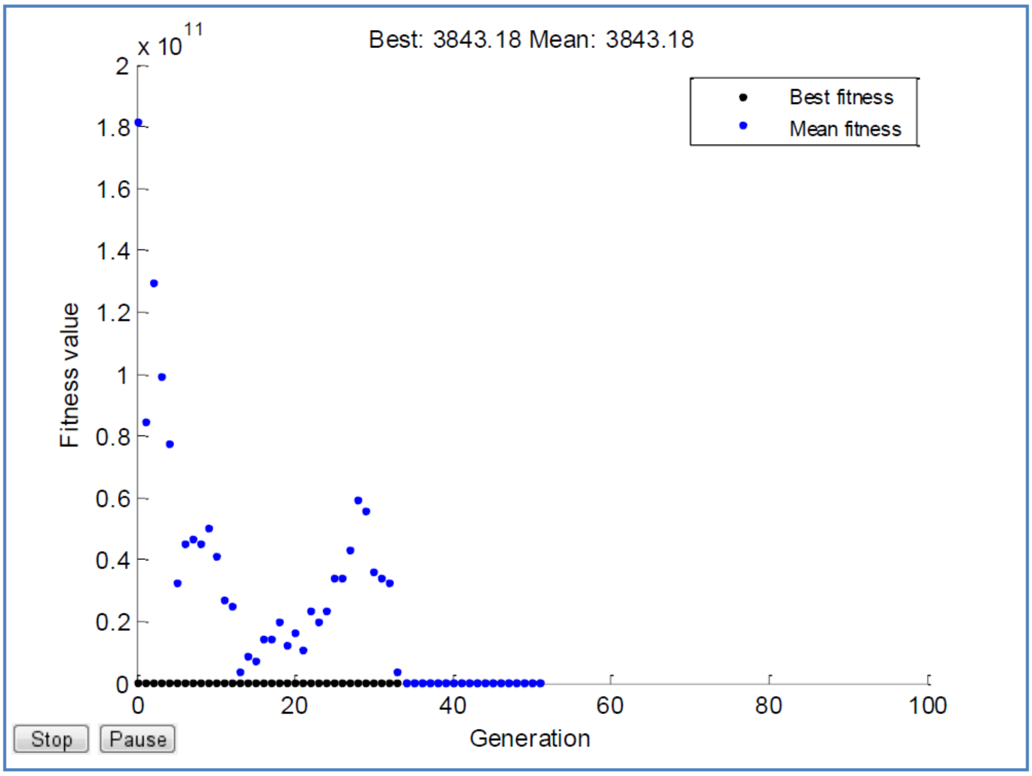


Figure 8-14 Progress of the optimisation model (test 2-1)

As shown on this diagram, the scenarios initially examined by the optimisation algorithm have high *Mean fitness* values up to around generation 35. From this point, all of the generated scenarios have resulted in significantly low fitness values; and the optimisation model finally stops just after generation 50 due to the average change in its fitness value being less than the predefined threshold of the optimisation algorithm.

The resulting optimum scenario is shown in Table 8-9: The start times of all schemes are outside the sensitive period which was specified on Figure 8-6. Furthermore all schemes under this scenario are performed in mode 1 (half link closure) in order to minimise disruption to the network.

Clearly the optimum scenario generated by the optimisation algorithm in this run cannot be the only optimum result. In fact all scenarios which avoid the sensitive period shown on Figure 8-6 and involve the operation of all links in mode 1 are likely have a similar disruption score, and therefore can be equally desirable.

For evaluating the reliability of the results, the optimisation algorithm is run 10 more times. Subsequently it was verified that the results of all runs are consistent with the one presented in the above table: all of the resulting scenarios have been shown to avoid the period with high time-sensitivity;

furthermore the vast majority of the links have been shown to be operating at mode 1 during the works.

Table 8-9 Optimisation results (test 2-1)

(The initial values set for the optimisation algorithm are shown in parentheses).

Scheme 1 Results								
Start Time	**Stage No**				**Mode No**			
S_1	$L_{1,1}$	$L_{1,2}$	$L_{1,3}$	$L_{1,4}$	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$
72(1)	2(2)	3(3)	1(1)	4(4)	1(0)	1(0)	1(0)	1(0)
Scheme 2 Results								
Start Time	**Stage No**				**Mode No**			
S_2	$L_{2,1}$	$L_{2,2}$	$L_{2,3}$	$L_{2,4}$	$M_{2,1}$	$M_{2,2}$	$M_{2,3}$	$M_{2,4}$
72(1)	2(4)	3(1)	1(2)	4(3)	1(0)	1(0)	1(0)	1(0)
Scheme 3 Results								
Start Time	**Stage No**				**Mode No**			
S_3	$L_{3,1}$	$L_{3,2}$	$L_{3,3}$	$L_{3,4}$	$M_{3,1}$	$M_{3,2}$	$M_{3,3}$	$M_{3,4}$
81(1)	2(2)	3(3)	4(4)	1(1)	1(0)	1(0)	1(0)	1(0)

8.2.3. Multi-objective optimisation test for deducing Pareto optimum points (test 2-2)

A common approach to deal with multi-objective optimisation models, as reviewed in Chapter 6, is to find a set of non-inferior – often referred to as *Pareto optimum* - solutions. As also reviewed in that Chapter, an optimisation model can potentially have an infinite number of Pareto optimal points. However a decision maker will be able to select a single solution from the Pareto points using methods such as the application of a utility function or the Analytical Hierarchy Processing methodology.

In this section, the multi-objective version of MATLAB genetic algorithm optimisation function is used to deduce a set of Pareto optimal points for three street works activities.

The start times of all schemes in this test are assumed to be limited between 40 and 60. This is mainly to assist with the graphical illustration of the optimum solutions; this is achieved by reducing the spread of the optimum points through limiting the range of one of the variables. The limited range of this variable should also allow for an easier comparison between the Pareto optimum results and a set of randomly generated scenarios.

The cost of undertaking the works is assumed to be £3000, £4000 and £5000 for schemes 1, 2 and 3 respectively and regardless of the traffic management modes. The duration of the works are assumed to be four days in mode 0 and five days in mode 1 for all of the schemes. The cost of delay in completion of the works, in reference to day 1 of the planning period, is assumed to be £10,000 per day.

The optimisation model took 117 seconds to complete due to reaching the maximum number of generations allowed (i.e. 50). Figure 8-15 shows the Pareto front which has been generated by the MATLAB genetic algorithm optimisation function.

The assumptions made for this test were meant to cause a conflict between the primary and secondary objective functions: The less disruptive scenarios are expected to correspond to street works with later start times (to avoid the time-sensitive period) and mode 1 of traffic management for the links. These scenarios however are expected to result in higher construction costs due to the delay in their completion and the longer duration of the works.

The extreme points on the leftmost and rightmost side of the diagram correspond to the scenarios which have led to optimising the model for one objective function, had the other objective function been ignored.

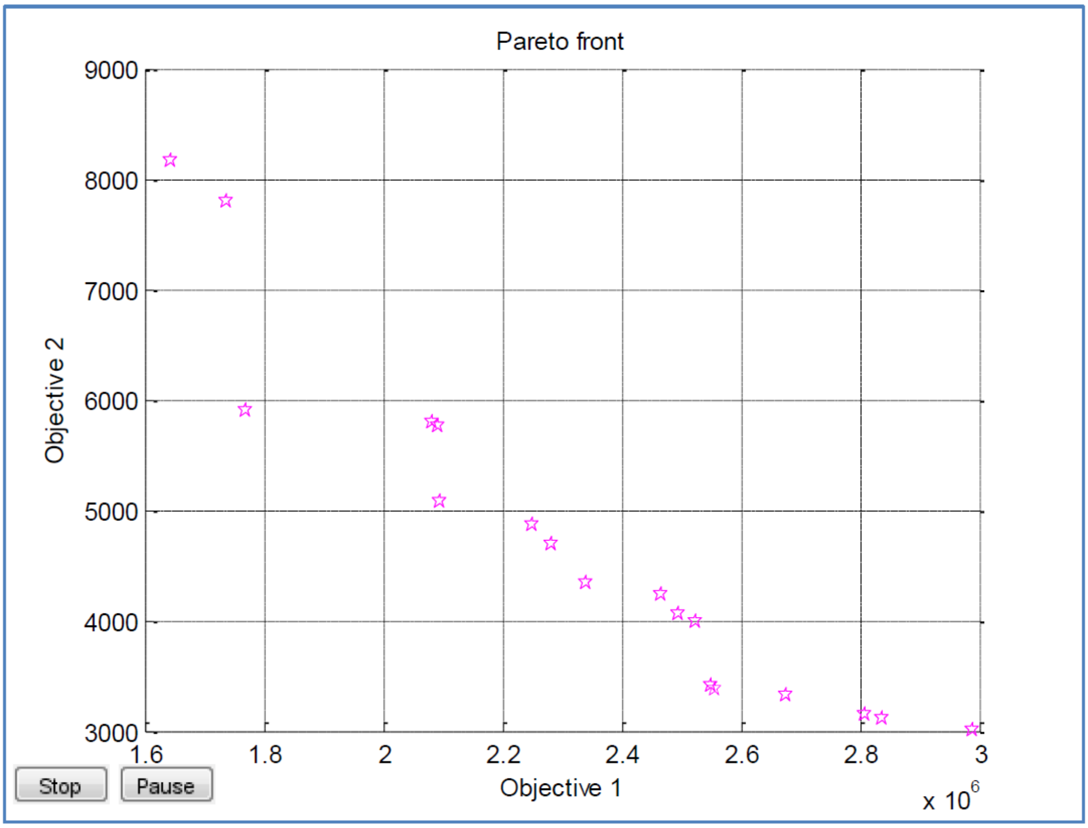


Figure 8-15 Pareto front points generated by MATLAB multi-objective genetic algorithm optimisation model (test 2-2)

In order to evaluate the robustness of the results, a separate script was developed to generate 100 random solutions for this multi-objective optimisation problem. This was intended to compare these randomly generated solutions with the Pareto solutions which have been generated by the optimisation model.

Figure 8-16 illustrates the points associated with the aforementioned two groups of scenarios.

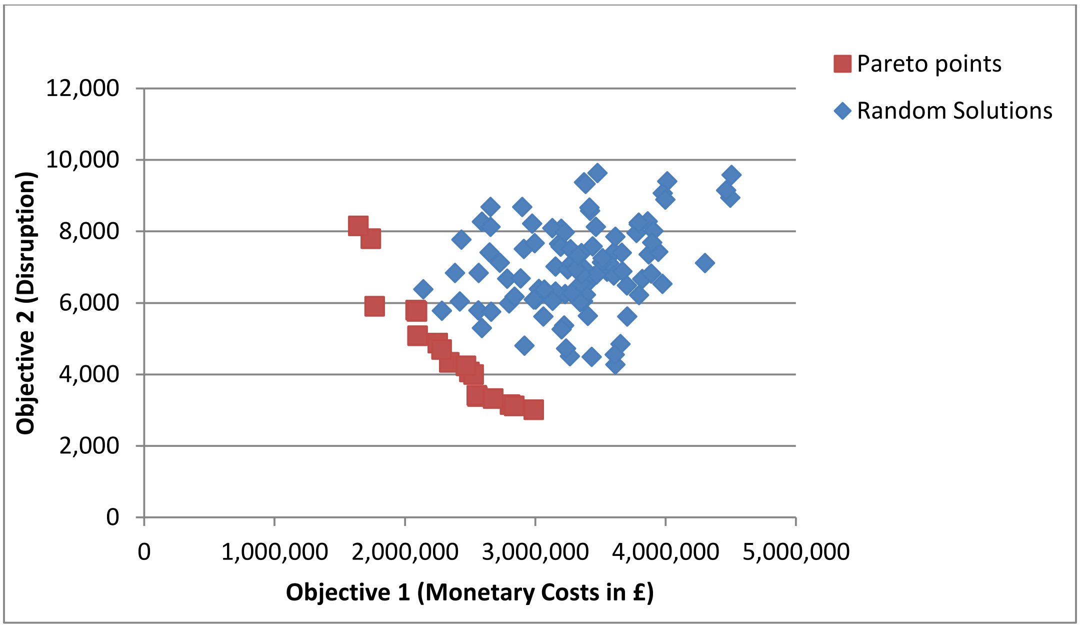


Figure 8-16 Comparison of Pareto points against randomly generated solutions (test 2-2)

It can be observed that all of the randomly generated points shown in blue colour, with no exception, are located **above** the Pareto set of points (i.e. being inferior to the Pareto points shown in red) . The results obtained clearly verify the robustness of the multi-objective optimisation model which was tasked to generate a set of optimum solutions that would be superior to all other feasible scenarios in the model.

8.2.4. Solving the multi-objective optimisation model by the weighted sum method (test 2-3)

The weighted sum method was introduced in chapter 6 as a simple and common approach to deal with multi-objective optimisation problems. It allows all objective functions of a multi-objective problem to be reduced to a single objective function. Subsequently the resulting problem can be solved by a suitable optimisation algorithm that is appropriate for single objective optimisation problems.

For undertaking the tests in this section, the fitness function of the optimisation model is modified in order to linearly combine the values of the objective functions with predefined weighting factors.

In order to evaluate the performance of the resulting optimisation model, two scenarios have been devised. Each scenario is associated with the scaling factor of one objective function significantly higher than that of the other objective function.

Once the performance of the optimisation model is verified for two extreme values of the scaling factor, one can be reasonably satisfied that the optimisation results for intermediate values of the scaling factors would be accurate too (validation and verification of the optimisation model were previously discussed in section 4.5).

The assumptions made for the duration and cost of the schemes are similar to those stated in the previous section.

In test a of this section (test 2-3a), each unit of disruption is assumed to be equivalent to £10,000 delay costs (i.e. a scaling factor of 0.0001 with reference to the primary objective function). This is to ensure that the optimisation model gives far more importance to the secondary objective function (i.e. minimising disturbance to the network) when calculating the value of the fitness function.

The optimisation algorithm took 113 seconds to complete. The progress of the optimisation algorithm for this test is illustrated on Figure 8-17, and the optimum scenario is presented in Table 8-10.

This figure shows that the *best and mean fitness* values of the fitness function quickly drop until around generation 25. Subsequently the optimisation model stops just after generation 50 due to the average change in the fitness value reaching the predefined threshold (i.e. 1e-6).

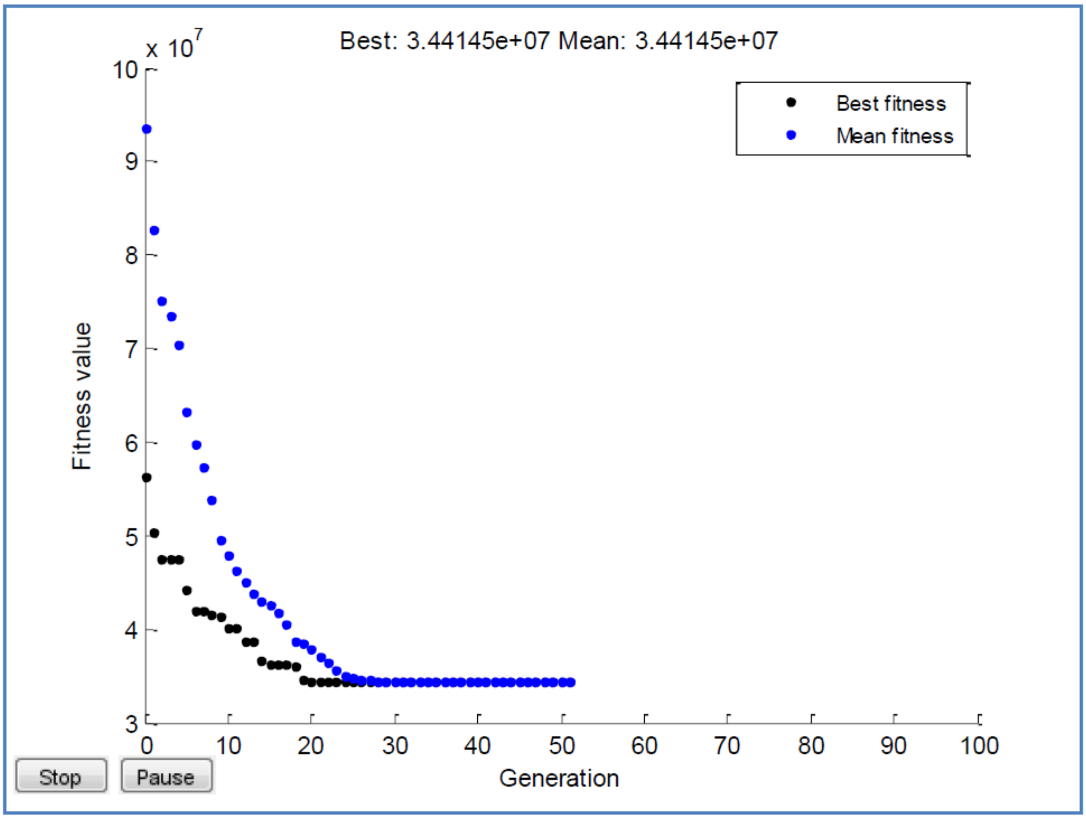


Figure 8-17 Progress of the optimisation algorithm (test 2-3a)
(one unit of disruption is assumed to be equivalent to £10,000 delay costs)

Table 8-10 Optimisation results for test 2-3a (multi-objective optimisation)

Scheme 1 Results								
Start Time	**Stage No**				**Mode No**			
S_1	$L_{1,1}$	$L_{1,2}$	$L_{1,3}$	$L_{1,4}$	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$
52	2	3	1	4	1	1	1	1
Scheme 2 Results								
Start Time	**Stage No**				**Mode No**			
S_2	$L_{2,1}$	$L_{2,2}$	$L_{2,3}$	$L_{2,4}$	$M_{2,1}$	$M_{2,2}$	$M_{2,3}$	$M_{2,4}$
53	2	3	1	4	1	1	0	1
Scheme 3 Results								
Start Time	**Stage No**				**Mode No**			
S_3	$L_{3,1}$	$L_{3,2}$	$L_{3,3}$	$L_{3,4}$	$M_{3,1}$	$M_{3,2}$	$M_{3,3}$	$M_{3,4}$
52	2	3	1	4	1	1	1	1

As expected, the optimum scenario belongs to a situation as if the optimisation algorithm were to minimise the secondary objective function only: All schemes have started almost as soon as the time-sensitivity level of the network drops to its minimum value (see Figure 8-6). Furthermore all but one link are operating in mode 1 (representing partial link closure) during the street works activities so as disruption to links and origin-destinations are kept minimal. This is due to the fact that the optimisation algorithm in this instance has been able to find a near optimum solution, rather than an optimum one.

In test b of this section (test 2-3b), each unit of disruption is assumed to be equivalent to £250 delay costs. Unlike the result of test 1, this low value of disruption is expected to make the minimisation of the primary objective function (associated with monetary costs) become the dominant factor of the multi-objective optimisation algorithm.

The optimisation algorithm took 100 seconds to complete for this test due to average change in the fitness value reaching to less than the predefined threshold. The progress of the optimisation algorithm is illustrated on Figure 8-18 and the optimum scenario is presented in Table 8-11.

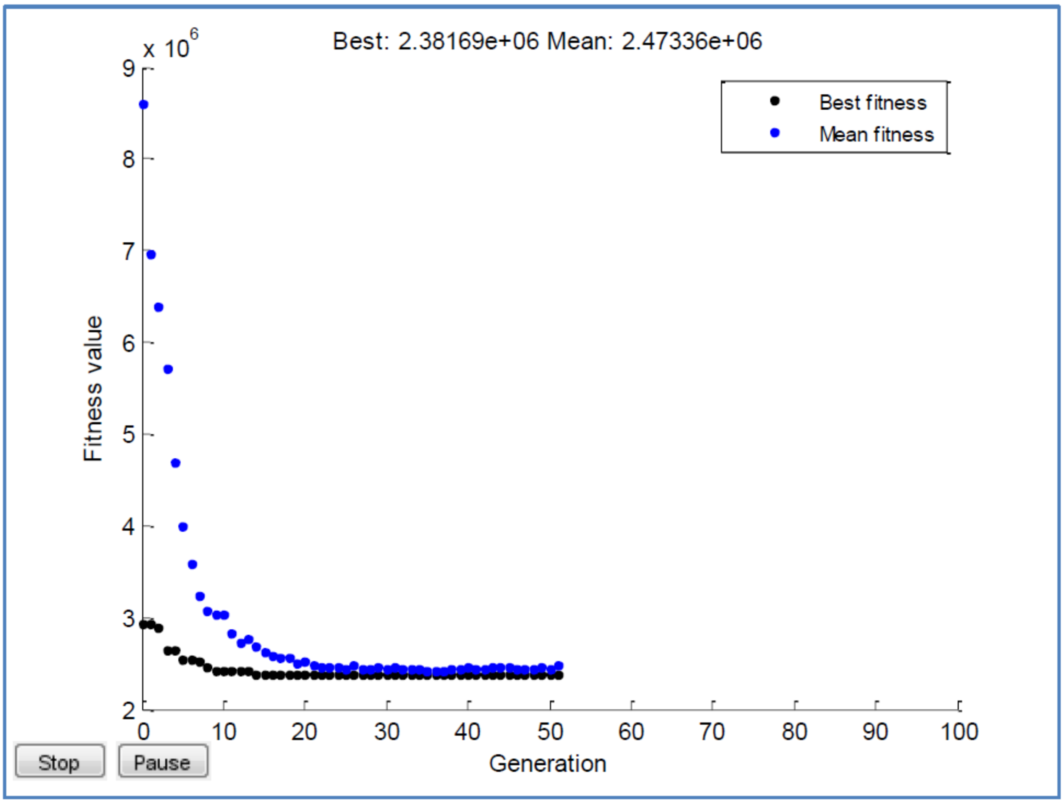


Figure 8-18 Progress of the optimisation model (test 2-3b)

All schemes have started as soon as they were allowed (i.e. on day 1) to avoid the costs of the late completion of the works. Furthermore all but one link are shown in the results as operating in mode 0 (associated with full link closure) during the street works activities in order to accelerate the completion of the works.

The optimisation algorithm has been repeated 10 times for both test 1 and test 2 to ensure the reliability of the results. The results of each run were shown to be very similar, in terms of start times of the schemes and link operation modes, to the results which were presented in in this section..

Table 8-11 Optimisation results for test 2-3b (multi-objective optimisation)

Scheme 1 Results								
Start Time	**Stage No**				**Mode No**			
S_1	$L_{1,1}$	$L_{1,2}$	$L_{1,3}$	$L_{1,4}$	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$
1	1	3	4	2	0	0	0	0
Scheme 2 Results								
Start Time	**Stage No**				**Mode No**			
S_2	$L_{2,1}$	$L_{2,2}$	$L_{2,3}$	$L_{2,4}$	$M_{2,1}$	$M_{2,2}$	$M_{2,3}$	$M_{2,4}$
1	1	2	3	4	0	0	0	1
Scheme 3 Results								
Start Time	**Stage No**				**Mode No**			
S_3	$L_{3,1}$	$L_{3,2}$	$L_{3,3}$	$L_{3,4}$	$M_{3,1}$	$M_{3,2}$	$M_{3,3}$	$M_{3,4}$
1	1	3	4	2	0	0	0	0

8.3. Applicability of the optimisation model to real size traffic networks

In fact most network design problem type of studies that are seen in the literature do **not** contain case studies (Farahani et al., 2013). The aforementioned authors note that this may be due to the fact that while these studies have focused on developing efficient solution methods for practical problems, usually they were not able to find the real data required for undertaking case studies (this was the case with the present study too). Nonetheless when relevant data do exist, the solution methods based on meta-heuristic optimisation algorithms have proved quite capable of efficiently solving bi-level optimisation problems (mainly emerging from network design problem studies) for real size traffic networks. Farahani et al. (2013) have listed a dozen of cases such as that of Agrawal and Mathew (2004) studying New Delhi network in India (containing 4076 links), and Yu et al. (2005) studying Dalian network in China (containing 3200 links).

As such, it would be quite sensible to claim that the optimisation algorithm developed in this study will be able to tackle real size traffic networks too once its performance is verified on a hypothetical test network.

There are a number of strategies to help reach better solutions (i.e. making the near optimum solutions closer to the theoretical optimum solutions) which are mentioned below. However these are rarely mentioned in academic works; this is because such academic works were mainly concerned with proving that a solution algorithm is theoretically robust following testing them on hypothetical or simplistic networks.

- Running the optimisation model several times with different initial population sets (see section 7.7). For some or all of the underlying decision variables, the initial population set may be selected from a different space of points (e.g. peak traffic times, and off-peak traffic times)
- Introducing a range of additional constraints and requirements to the optimisation algorithm based on practical considerations and ‘common sense’-based forecasts about the final solutions. This can help the optimisation algorithm run more efficiently by searching for solutions in the regions which are more likely to include the optimum points.
- Undertaking sensitivity tests to establish an approximate relationship between the duration of a run of the optimisation algorithm, and the quality (in terms of the value of the fitness function) of the solutions produced by the optimisation algorithm. A trade-off normally exists between the maximum duration allowed of an optimisation run, and the quality of the solution points produced by the optimisation algorithm.

8.4. Chapter concluding remarks

This chapter was dedicated to undertaking a number of experimental tests in order to evaluate the effectiveness of the proposed genetic algorithm solution methodology which was presented in chapter 7.

In order to verify the viability of the optimisation algorithm, the experimental tests in this chapter were devised in such a way that the approximate values of the optimum results could be logically estimated in advance.

For the multi-objective optimisation algorithm, the results were tested against the fitness values of a large number of randomly generated scenarios to ensure that the scenarios generated by the optimisation algorithm were superior to the randomly generated solutions.

For every test associated with either a single-objective or multi-objective optimisation problem, the optimisation algorithm was shown to be able to constantly progress towards the more desirable scenarios, and eventually produced an optimum or near optimum scenario. The resulting Pareto points generated by the optimisation model was also shown to be superior to all of the randomly generated solutions.

As the performance of the optimisation model has been verified in this chapter, it will now enable network planners to schedule a set of street works activities in such a way that the overall monetised costs and non-monetised disruptions incurred by all of the stakeholders are minimised. This goal could not have been achieved prior to the availability of the optimisation model and its embedded solution algorithm which were developed in this study.

Chapter 9
Thesis Conclusions

9.1. Introduction

This chapter summarises the outcomes of the present research, and evaluates them against the objectives which were set out in chapter 1.

First, the key achievements of this research are highlighted in section 9.2 in relation to each research objective. Next in section 9.3 validation statements are provided for the outcomes of this study. Finally in section 9.4 a number of areas for future work are identified to address the main limitations of this study.

9.2. Outcomes of the study

9.2.1. Objectives 1: Literature review on the practice of street works, and relevant transportation studies concerned with analysing degraded networks

Chapter 2 looked into the issues and costs arising from undertaking a huge number of street works in the country every year in order to maintain the vital utilities and highway infrastructure for residents and businesses. Next it reviewed the practice of street works in the United Kingdom, including the relevant legislation and codes of practice.

The review identified the coordination of street works schemes as a vital means of minimising the adverse effects of street works, the two most significant ones mentioned in the relevant literature are the costs and disruption caused to society. Within this coordination context, the literature review revealed a sincere aspiration for *optimising* the underlying features of street works schemes, not least the timing of the schemes and the layout of the areas on the roads which should be temporarily closed to the road users. Although some limited guidance for evaluating the local impact of street works does exist, nonetheless no overarching framework was found in the literature which could assist with such an optimisation exercise on a network-wide scale.

Chapter 3 reviewed five types of transport network analysis models, including traffic assignment models; reliability, vulnerability, and accessibility of traffic networks; and network design problem studies. The review later helped this study (in chapters 4 to 7) with identifying which themes of these studies may sensibly be incorporated into an optimisation model which is concerned with scheduling of street works. This mainly included:

- Identifying those types of traffic assignment models which are most suitable for analysing degraded network conditions and their associated assumption in relation to traffic behaviour (section 3.1).
- Identifying how journey time reliability can be measured and incorporated into traffic assignment models (section 3.2.2).
- Identifying a journey time reliability indicator which can be used to represent the relative importance of network links (section 3.2.3).
- Identifying the generic mathematical formulation of those transport studies which are concerned with optimising configuration of transport networks and associated network improvement investments (section 3.3).

The literature review conducted in this thesis made it possible for the first time to study the practical aspects of street works schemes (objectives, legislation, constraints, etc.) in connection with the relevant subjects in academic transport studies (e.g. distribution of traffic in degraded transport networks, and assessment of accessibility and vulnerability of traffic networks). The consideration of the relevant elements of the existing practice and literature which were reviewed in chapters 2 and 3 proved essential for formulating the street works optimisation model in the following chapters of this study.

9.2.2. Objectives 2: measuring the effects of street works schemes

In chapter 5 it was argued that the effects of street works schemes should be categorised to monetised and non-monetised effects, each of them was explained by an objective function which is sought to be minimised by the optimisation model:

First, the study created a primary objective function in order to capture the monetised costs of street works schemes which are incurred by the stakeholders. These costs, listed as follows, were generally identified in the literature concerned with evaluation of highways improvement and maintenance projects:

1. cost of delays to road users, vehicle maintenance costs, and cost of increased accidents
2. cost of street works activities and the necessary traffic management arrangements.

3. Cost of the losses (including loss of benefits) incurred due to late completion of street works schemes.

Second, this study highlighted a gap in the academic literature with respect to the non-monetised effects of street works activities which are characterised by short term traffic restrictions. It was argued that most network performance indicators found in the literature, e.g. accessibility and vulnerability indicators reviewed in chapter 3, in their own rights are <u>not</u> the main concern of planners during scheduling of temporary road restrictions which are required for undertaking street works schemes. Rather, this study shed light on the notion of *disruption* which is the primary focus of planners during the process of scheduling street works schemes. The review in this chapter demonstrated that the disruptive effects of street works on the users of links and travellers between origins / destinations of a network are a major consideration during the planning process of any activities which could temporarily reduce the capacity of a transport network. Despite being an abstract subject, disruption still needs to be measured in an appropriate way in order to be incorporate into the optimisation model of this study.

As a result, this study developed a novel fuzzy logic based method in order to measure the disruptive effects of street works schemes which are not commonly captured as monetised costs.

The fuzzy logic inference system developed in this thesis mainly consists of:

- The fuzzy variables (embedding several fuzzy membership functions) which are associated with the *time-sensitivity* of disruptive events, *accessibility degradation* of links, and *connectivity degradation* of the origin-destinations of the network. The aforementioned are found to be the main factors in determining the level of disruption caused to the users of a transport network.
- A set of fuzzy rules which are used to infer a disruption index for all links and origin-destinations of the network based on the values of the fuzzy variables.

Devising a robust and flexible methodology to measure disruption to transport networks is a major contribution of the present thesis to transport network studies. This ‘fuzzy system’-based assessment method guarantees maximum flexibility in catering for varying types and levels of priorities, tolerance and evaluation methods which prevail among different network authorities in relation to disruptive street works. Without the need to change the general form of the fuzzy model presented here, different rules, weighting factors, and membership functions can be used to account for the aforementioned differences when inferring a disruption index for every link and origin-destination of the network. Such flexibility was unlikely to be available by conventional evaluation methods such as linear or polynomial functions.

9.2.3. Objectives 3: expressing the optimisation problem in mathematical terms

In chapter 5, the optimisation problem of this study was formulated as a *bi-level programming* class of optimisation problems. This study demonstrated that the higher level of the street works optimisation problem involves deciding on how to change the configuration of a network, mainly through the type and duration of the traffic management schemes associated with street works schemes, so that the objectives of the optimisation model are minimised. Subsequently in the lower level of the problem, the road travellers will have to adapt their route choices based on the new network conditions. The resulting delays to the affected travellers can be deduced by applying an appropriate traffic assignment model to the degraded network.

In chapter 6 it was reviewed that this type of problem has been extensively studied in the context of transportation related subjects in terms of how to choose suitable solution algorithms to suit their underlying characteristics. Equally, formulating the optimisation problem of this study as a bi-level optimisation problem assisted with selecting a suitable solution methodology for it (presented in chapter 7).

This study was mindful from the outset that street works activities are quite diverse by nature. Therefore unlike the models (e.g. specific mathematical equations) found in the literature which only suit limited types of highway maintenance activities, this study formulated street works schemes as a general *project scheduling model*. Doing so, the duration and cost of activities on each link will depend on the *resource modes* which are selected for each task, i.e. type of traffic management strategy, number of crew allocated to each scheme, etc. This formulation provides maximum flexibility to the optimisation model of this study in order to suit any type of activities which can affect the capacity of a network, such as utility works and highways and infrastructure improvement projects.

Thanks to the work conducted in chapters 5 and 6 to meet the second and third objectives of this study, for the first time the street works optimisation problem was materialised from a rather vague idea which had been mentioned in a few good practice documents into a robust and structured mathematical optimisation problem. The objectives of the optimisation problem, and how to measure them, the levels of the optimisation problem, and the most underlying decision variables sought to be optimised became all clear as a result of this work.

9.2.4. Objective 4: finding a suitable solution methodology for the street works optimisation problem

In chapter 7, this study demonstrated that the street works optimisation problem is a *non-convex* and *NP-hard* bi-level optimisation problem, and therefore entails the application of a *meta-heuristic* optimisation method such as the genetic algorithms. This enables the optimisation algorithm to search around various local optimum points, one of which can be the optimum scenario among the entire space of candidate solutions.

This thesis identified *genetic algorithms* as a very suitable methodology for solving bi-level optimisation problems due to having a number of outstanding characteristics which were reviewed in chapter 7. The suitability of this methodology for solving the optimisation problem of this study is also supported by the successful application of genetic algorithms in many other bi-level or non-convex optimisation problems in various transportation-related studies which were mentioned in chapter 7.

9.2.5. Objective 5: developing a bespoke solution algorithm for the street works optimisation problem

The study was mindful that for some types of optimisation problems, the genetic algorithm methodology should first be tailored for the specific optimisation problem under question. This includes the optimisation problem of this study which embeds discrete type of variables. In this study, the MATLAB language programme (MathWorks Inc., 2014d) and its genetic algorithm optimisation function were used to develop a bespoke solution algorithm for the optimisation problem of this study.

As such, in chapter 7 the study devised a bespoke solution algorithm based on the genetic algorithm methodology for the street works optimisation problem. The following were the key components of developing this solution algorithm:

Adapting genetic algorithm to the discrete type of variables:

All types of meta-heuristic optimisation methods, including genetic algorithms, have been devised to work with continuous types of variables in their original formats. As such, the study developed and presented a simple methodology for mapping the random values originally generated by the optimisation algorithm to suitable and meaningful discrete values, and in such a way that the random distributions embedded in the genetic algorithm processes are not distorted.

Devising the structure of the genetic algorithm chromosomes (representing candidate solutions):

This study devised a suitable structure for the individual chromosomes which are continually generated and then evaluated by the optimisation algorithm during an optimisation run (chapter 7). The genes of a chromosome correspond to the decision variables of street works schemes, including the start times of the schemes, sequence of individual links subject to the schemes, and traffic management strategies selected for network links. This structure can be easily expanded if additional variables (e.g. duration of *idling periods* during undertaking a scheme) are needed. It also assists with modelling situations where two or more schemes can be undertaken on a link at the same time.

The study also proposed a robust way, through using dummy random variables, by which the chance of the *preferred scenarios* in the optimisation algorithm are increased. This is expected to reduce the running time of the optimisation algorithm for reaching the optimum or near optimum solutions in many circumstances.

Development of the fitness function:

The fitness function of the optimisation model is primarily meant to compute the values of the objective functions of the optimisation model. However to enable the optimisation algorithm to work efficiently, the fitness function was devised in such a way it can perform the following additional tasks:

- Mapping the continuous random numbers generated by the genetic algorithm function at each generation to appropriate discrete numbers, which can then be associated to the underlying decision variables of the optimisation model.
- Identifying non-feasible candidates (e.g. due to conflict between two incompatible schemes) and penalising them with a penalty value.
- When appropriate, converting non-feasible or less-desirable chromosomes to feasible or more desirable chromosomes in order to enhance the performance of the optimisation algorithm.

The optimisation problem studied in this thesis required a **tailored** meta-heuristic optimisation algorithm which did not exist in the literature before. This mainly consisted of devising a robust structure for the candidate solutions (genes), and defining suitable tasks for the fitness function of the genetic algorithm in order to enable it to deal with the optimisation problem of this study. The outcome of the work conducted in chapter 7 provided the street works optimisation problem with a viable solution methodology which promises to find optimum or near optimum values for the underlying decision variables of the street works optimisation problem.

9.2.6. Objective 6: Verifying the performance of the optimisation model by experimental tests:

In order to verify the performance of the optimisation model, in chapter 8 the study devised several tests using a small hypothetical network and three street works schemes. The study argued that for the purpose of evaluating the optimisation algorithm, using a small hypothetical network was more suitable than a realistic size one. It was noted that this approach is quite common with the majority of network design problem type of studies observed in the literature which used meta-heuristic type of algorithms to solve bi-level optimisation problems (as does the optimisation model of this study). Similarly, the present study claims that the optimisation algorithm developed in this study will be able to tackle real size traffic networks too, once its performance is verified on a hypothetical test network.

Single objective optimisation experiment: In sections 8.1.3 and 8.2.2, the optimisation algorithm was run for each of the objective functions separately. For all of the tests carried out, the progress diagrams showed the optimisation model steadily moving from evaluating non-feasible or non-desirable scenarios towards more desirable scenarios, and finally stopping due to meeting one of the termination criteria. This pattern verifies the robustness of the single-objective optimisation algorithm.

The *near optimum* values obtained from the optimisation algorithm were shown to be reliable based on the optimisation model inputs relating to the properties of the network, traffic data, and the street works schemes. For each test, the optimisation algorithm was repeated 10 times (i.e. 10 runs) to calculate a *relative standard deviation* for the fitness function values of the runs. For each test (comprising 10 runs), the relative standard deviation which was calculated for the results was shown to be less than 15%. This is deemed acceptable for constituting near-optimum results.

Multi-objective optimisation experiment – 'Pareto front' approach tests: In section 8.2.3, the multi-objective optimisation algorithm successfully produced a set of Pareto optimum solutions, also referred to as a *Pareto front*. In order to test the accuracy of the results, the Pareto points were compared against 1000 randomly generated feasible solutions to the optimisation problem. The Pareto points proved superior over all of the randomly generated points. This proves the robustness of the multi-objective optimisation algorithm of this study.

Multi-objective optimisation test – 'weighted sum' approach tests: In section 8.2.1, the fitness function of the optimisation model was modified to combine the values of the objective functions with a linear equation that uses predefined weighting factors. Two tests were undertaken, each test associated with the scaling factor of one objective function significantly higher than that of the other objective function. This, together with the assumptions made for the properties of the street works schemes, made it possible to predict the range or exact values of the optimisation variables which would minimise the objective functions for each test. In order to make finding optimum solutions harder for the optimisation algorithm, the *initial population* devised for the genetic algorithm at each test was deliberately set to fall outside the desirable region of the variables subject to optimisation (e.g. the schemes were set to start at peak days to generate high delay costs).

In each test, the optimisation algorithm showed steady progress from outside the solution region towards the solution region, and produced the optimum results which had been predicted in advance. These results verify the robustness of the optimisation algorithm of this study.

Following the work conducted in chapter 8, the solution algorithm which was devised in this study is verified for solving both single objective and multi objective street works optimisation problems. As a result this solution algorithm can be confidently used by planners to optimise the characteristics of a number of street works schemes in a traffic network.

9.2.7. Significance of the outcomes of the present study to the theory and practice of street works coordination

To the author's best knowledge, no theoretical or practical framework was previously available to enable planners to optimise the properties of street works schemes in a traffic network based on:

- a model founded in robust optimisation theories;

- and a model which at the same time can measure and reflect those costs and disruptive effects of street works which matter most to the stakeholders of street works activities during the process of a scheduling exercise.

The optimisation model devised in this study enables network planners to schedule a set of street works schemes in such a way that the overall costs and disruptive effects of street works schemes are minimised at the same time. This inevitably entailed devising a methodology for measuring *disruption* to traffic networks in this thesis, since other network performance indicators found in the literature were deemed unsuitable to serve as the objective function of a street works scheduling model.

If the optimisation model of this study is upgraded to a commercial software package, it can lead to significant benefits for road users and communities which are frequently affected by street works schemes.

9.3. Validation statements

Validation is claimed for this study based on the following arguments which are taken from the relevant chapters of this thesis (chapter 5 to 8).

9.3.1. Robustness of the formulation developed for the optimisation model of this study (chapter 6)

The resulting bi-level programming formulation of the optimisation problem is fully consistent with that of some of the most well-known classes of optimisation problems in transport studies, including the *network design problem* studies. A common theme of these studies is the interaction between the objectives of the network users and network planners at two different levels:

On the higher level, network planners decide on changing the condition and configuration of the network. In the next level of the problem (the lower level), road travellers adapt their route choices based on the new state of the network. In chapter 6, this phenomenon was justified to be the prevailing condition for the optimisation problem of this study too.

9.3.2. Appropriateness of the method devised for measuring the disruptive effects of street works activities (chapter 5)

In chapter 5, the study argued that the disruptive effects of street works are best explained in qualitative terms. This is due to the fact that the overall disruption effects incurred by network users due to degraded links and origin-destination movements are dependent upon imprecise and subjective variables such as *importance* of the time of disruptions, *level of accessibility degradation,* and t*he level of connectivity degradation*.

The literature review in chapter 5 revealed that *fuzzy theory* is arguably the most suitable methodology to deal with parameters (i.e. variables and relationships) that have characteristics such as impreciseness, subjectivity, and uncertainty. This is supported by concrete evidence obtained from successful application of fuzzy theory to solve a truly wide range of classic and modern transportation related problems which encompass such parameters, some of which were introduced in chapter 5. Therefore this study argues that devising a fuzzy inference system is the most suitable approach to measuring the *disruptive effects* of street works schemes on the users of a traffic network.

9.3.3. Suitability of the solution methodology devised for the optimisation problem of this study (chapter 7)

Bi-level optimisation problems are well-known to be solvable by using meta-heuristic search types of algorithms, such as genetic algorithms. In order to single out the most suitable meta-heuristics for a given bi-level optimisation problem among two or more types of algorithms, one should normally compare their performance on a given problem through undertaking an extensive number of experimental tests. Such a comparison study was beyond the scope of the present thesis. Nonetheless the review conducted in chapter 7 made it clear that among the available meta-heuristics, genetic algorithms appeared to be the most common optimisation techniques with a range of unique or rare desirable properties. The review found that genetic algorithms have been applied to extensive types of NP-hard or non-convex problems with success. This includes the *work zone optimisation problems* which are the closest types of transportation studies to the problem studied in this thesis. Genetic algorithms have also been applied to solve various versions of the well-known *network design problems*, which are similar to the optimisation problem studied in this thesis due to the prevailing trade-off between the objectives of the network planners and the highways works undertakers.

9.3.4. Satisfactory performance of the optimisation algorithm (chapter 8)

The progress diagrams generated for the optimisation runs of each test illustrated that the value of the fitness functions, after a number of initial generations, continually decrease towards the later generations until they stop due to reaching a termination criteria.

For each optimisation test, the values of the initial population were deliberately selected to fall outside the solution region of the variables subject to optimisation.

In each test, the optimisation algorithm showed progress from outside the solution region towards the solution region, and produced the optimum results which had been predicted in advance.

The Pareto optimum points generated by the multi-objective optimisation runs were compared against 1000 randomly generated feasible solutions to the optimisation problem. The Pareto points proved to be superior to all of the randomly generated points without any exception.

For single-objective optimisation tests, the optimisation algorithms were executed 10 times (for each test) to measure the relative standard deviation (RSD) of the fitness function values. For all of the tests, each comprising 10 runs, RSD proved to be less than 15%, thus confirming the reliability of the optimisation algorithm in producing near optimum results.

9.4. Future works to address limitations of this study

The following sections describe several areas for future research which have been identified in relation to the main limitations of the present study (as mentioned in various sections of this thesis).

9.4.1. Undertaking a case study

It was not possible for this thesis to include a case study with real street works schemes and a realistic size traffic network. Such a case study may particularly help with establishing the size of savings which can be expected from using this optimisation model to schedule street works schemes of a traffic network.

However undertaking a case study is likely to require the optimisation model of this study to be upgraded to meet the professional standards found in a commercial package first, and to address some of the constraints which are identified in the next sections of this chapter. Furthermore the process of obtaining required data from all of the street works undertakers can be a complex and lengthy exercise, as many undertakers are unable to provide, or reluctant to reveal, the information which are needed as inputs to the optimisation model.

9.4.2. Improving the performance of the optimisation algorithm

Several potential areas for improving the performance of the optimisation algorithm which was developed in this thesis are identified as follows:

- For some problems, a genetic algorithm can reach the region near an optimum point relatively quickly, but it can take many function evaluations to achieve convergence. It is noted that (MathWorks Inc., 2014c) a commonly used technique is to run the genetic algorithm function for a small number of generations to get near an optimum point. Then the solution from the genetic algorithm is used as an initial point for another optimisation solver (i.e. a local optimisation algorithm) that is faster and more efficient for local search. The potential benefits of adopting such a hybrid solution approach for the underlying problem of this thesis could be the subject of an investigation.
- In chapter 7 (section 7.1.2), it was reviewed that the stochastic ranking method proposed by Runarsson and Yao (2000) can have major advantages over the commonly used penalty function method in order to speed up the process of reaching the optimum solutions. It would be worthwhile investigating this further by a number of experimental tests.

  Parallel computing (or processing) is defined as the simultaneous use of multiple computer resources to solve a problem in order to obtain results faster. The idea is based on the fact that the process of solving a problem can be divided into smaller tasks, which may be carried out simultaneously with some coordination Yang (2010). This author (Yang, 2010; pp. 167-168) also notes that population-based algorithms such as genetic algorithms are particularly easy to implement and promise substantial gains in performance because the procedure of evaluating multiple solutions is naturally prone to parallelism. As such, parallel computing is quite likely to benefit the optimisation algorithm which was developed in this study, and therefore is an attractive area of further modelling work (parallel processing is supported by MATLAB global optimisation toolbox which was used for developing the optimisation algorithm of this study).

9.4.3. Expansion of the type of decision variables which can be subject to optimisation

A good number of additional decision variables can be envisaged for incorporation into the optimisation model in order to suit a wider range of real-world circumstances. A number of examples are:

- A Boolean variable to decide whether a scheme should be undertaken during day or night (overnight working shifts are more expensive but cause less disruption)
- In addition to the start day of each scheme, new variables to define the start time of each scheme during a working shift
- A variable to represent the number of idling shifts for each scheme
- A variable to choose between two or more **alternative** street works schemes (e.g. in circumstances where a client has two or more options for undertaking some maintenance activities on part of a traffic network)
- In urban environments partial or complete closure of junctions are often the most disruptive type of street works – to the author's experience as a road engineer - as they often lead to the closure of several links at the same time. To cater for circumstances where one or a number of **road junctions** become subject to street works, additional variables to the optimisation model should be introduced. This needs to be in such a way that the traffic management strategy for a junction will trigger a change to the state of the links which connect with that junction. The traffic assignment model of the optimisation algorithm should also be adapted to deduce the new traffic patterns following the closure of a junction.

Increasing the number of decision variables will increase the time required for completion of an optimisation run. As such, it will be beneficial to investigate the time required for the completion of an optimisation run based on factors such as the number of decision variables, size of the network, etc. In doing so, one can look into this aspect for similar types of transportation modelling works, for example *network design problem* studies which were reviewed in chapter 3.

9.4.4. Provision for street works activities which can be cancelled, or deferred to future years

Completion of all street works schemes within a single planning period (e.g. a calendar year) was assumed compulsory for the optimisation model of this study. However, it may be possible to schedule a set of street works schemes for two or more planning periods. In such a way, a street works scheme can be deferred from the first planning period to a subsequent one. For instance this is quite common with highway maintenance activities which can be evaluated and planned several years in advance. For instance a study by

Yang (2010) has provided two separate formulations for optimising work zone characteristics in single and multiple planning periods.

Developing an additional formulation for the optimisation model of this study to cater for multiple planning periods will be an interesting area for further work.

9.4.5. Choosing the right type of traffic assignment model for the optimisation model

The literature review conducted in chapter 2 made it clear that choosing a type of traffic assignment model suitable for degraded traffic networks is very important for complementing the optimisation model of this study:

The traffic assignment model should be able to predict the traffic flows on the network links accurately under degraded conditions, thus enabling the optimisation model to accurately calculate the cost of delays which are incurred by the road users. Furthermore solving some types of traffic assignment models are quicker than others, in particular for realistic size traffic networks, potentially resulting in a lot of difference with the speed of the optimisation model runs. Therefore conducting a study to investigate into different types of traffic assignment models, particularly those which are most suitable for degraded traffic networks, and to evaluate their suitability for the present optimisation model is deemed highly beneficial. This should include the outcomes of the DISRUPTION Project (Marsden et al, 2014) which aims at understanding the impacts of disruptive events upon people's travel behaviour.

In chapter 6, another challenge in relation to the application of traffic assignment models was highlighted. In order to increase the speed of the optimisation algorithm, it will be necessary to minimise the number of times that the traffic assignment model should run at each generation. In some circumstances, it may be unnecessary to run the traffic assignment model for deducing traffic flows on some network links, thus saving time for execution of the optimisation algorithm. Devising a methodology to identify such circumstances within the optimisation model, and comparing different existing methodologies to address this issue, will be highly beneficial for increasing the speed of the optimisation algorithm. In doing so, the outcomes of a PhD thesis (Gemar, 2013) which has studied *sub-network* analysis of traffic networks by using dynamic traffic assignment models can be valuable. It is also reminded that in chapter 6 two studies were identified (Chen et al., 2012; Zheng et al.,

2014) which have addressed this issue for network vulnerability assessment models, and work zone scheduling problems.

Appendix A
Complementary information about fuzzy inference systems

This section contains a brief review of the fuzzy logic inference system concepts and procedures in relation to developing the secondary objective function of this report which was dealt with in chapter 5.

The fuzzy set theory is largely attributed to Zadeh (1965) who introduced the concept of fuzzy sets, whereby members of a given set can belong to that set with different levels of membership between 0 to 1. A comprehensive review of fuzzy sets and fuzzy logic theories, including the history of their applications in transport studies, can be found in many references (e.g. Teodorovic, 1998; Hanss, 2005; MATLAB Fuzzy Logic Toolbar User's Guide, 2014a). The following sections focus on reviewing a fuzzy inference system, which is a system that uses fuzzy set theory to map *inputs* to *outputs*. Fuzzy inference is the process of formulating a mapping structure, using fuzzy logic rules, in order to deduce an output from the inputs of the inference system.

A.1 Fuzzy membership functions

For the interference system used in this study, the initial input values are expressed by numerical crisp values belonging to the range of 0 to 10. The relevant fuzzy membership functions will then be used to infer the membership degree of an input value associated with a fuzzy variable.

Many different types of fuzzy membership functions are available which poses different characteristics, and can be suitable for different applications. The following diagrams show several common types of membership functions:

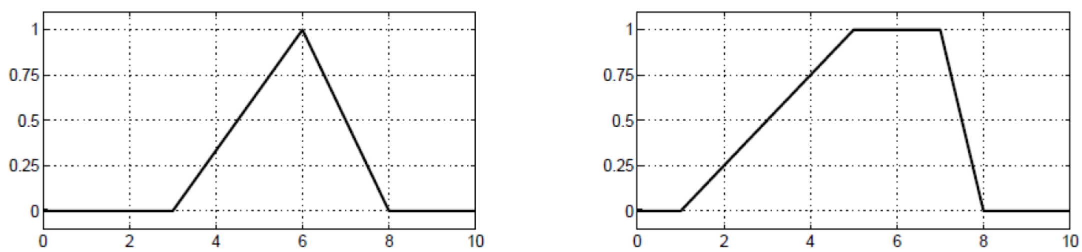


Figure 0-1 Triangular (left) and trapezoidal (right) membership functions (characteristics: formed by simple straight lines)

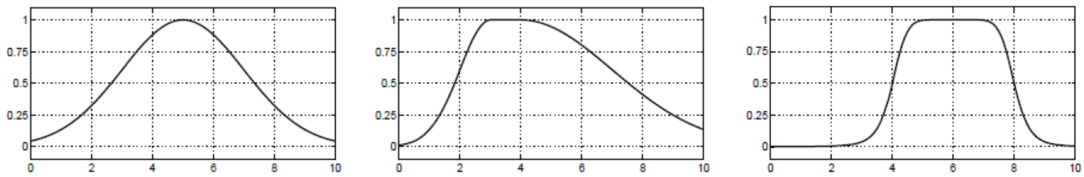


Figure A-2 Gaussian and bell (the right-most picture) membership functions

(characteristics: have the advantage of being smooth and nonzero at all points)

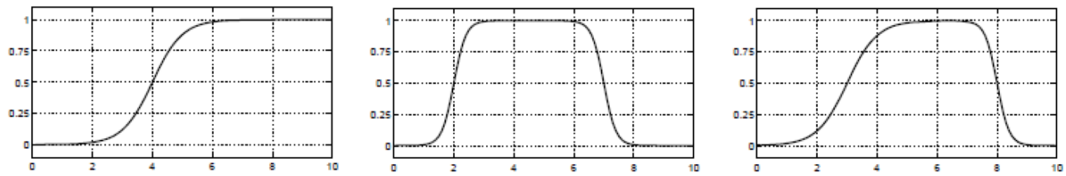


Figure 0-3 Sigmoidal membership functions

(characteristics: able to represent asymmetric properties)

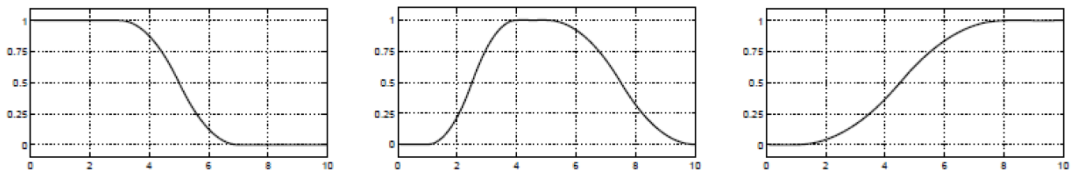


Figure A-4 Polynomial based membership functions

(characteristics: able to represent asymmetric properties)

A.2 Introduction to Mamdani Inference System procedures

The fuzzy inference process adopted in this study is called the Mamdani inference system which is the most widely used fuzzy inference system and is supported by MATLAB Fuzzy Logic Toolbox Manual (MathWorks Inc., 2014a). It is based on the work mainly attributed to the late Professor Mamdani (e.g. Mamdani & Assilian, 1975) and has a five-step procedure to deduce an output value from the input values. These steps have been briefly described below based on an example taken from the aforementioned reference for deducing the appropriate amount of tip to a waitperson in a restaurant. It consist of two input variables (i.e. *service quality* and *food quality*), the following three fuzzy rules, and the membership functions which are shown on Figure A-5.

- If service is poor or the food is rancid, then tip is cheap
- If service is good, then tip is average

If service is excellent or food is delicious, then tip is generous

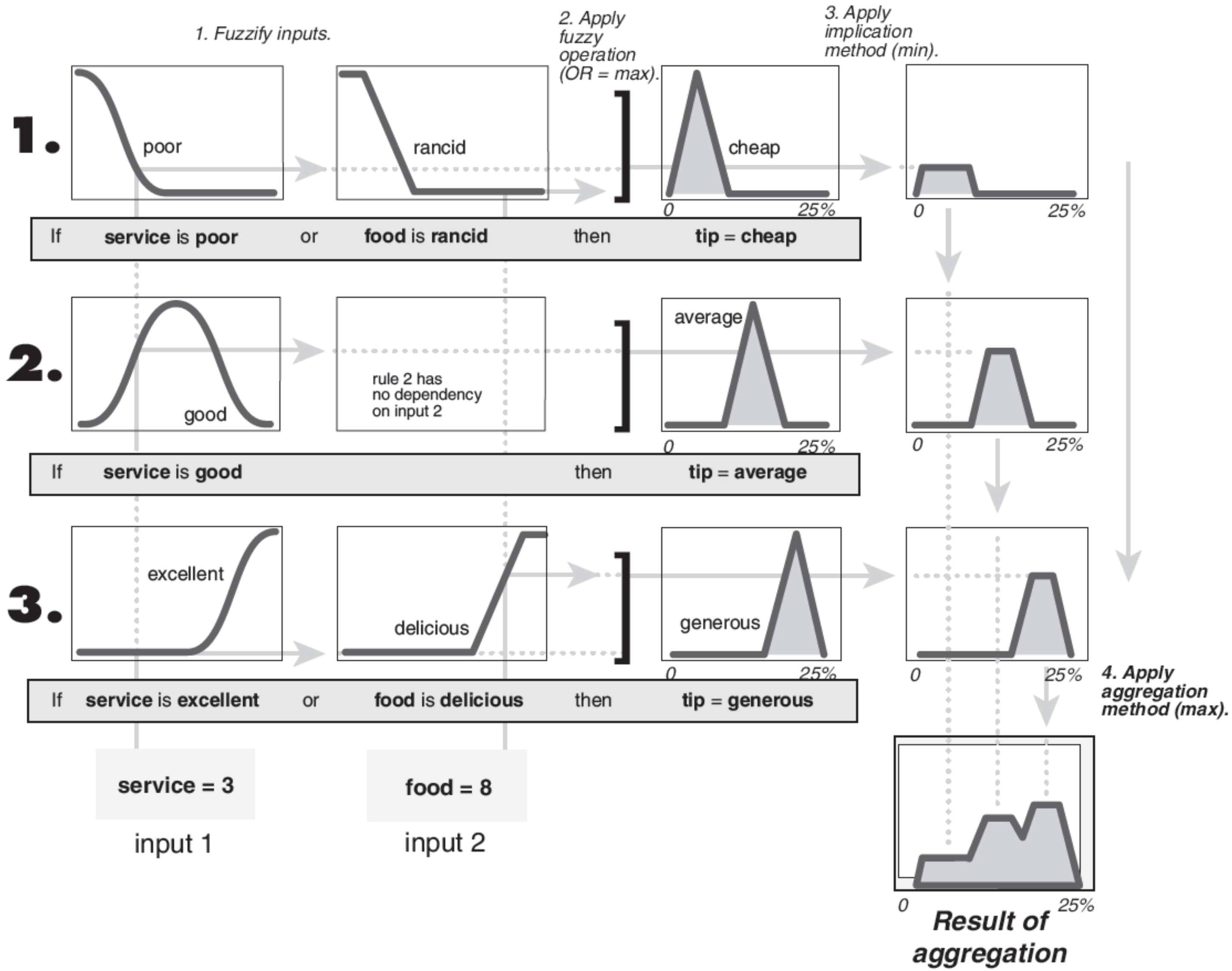


Figure A-5 The application of Mamdani fuzzy inference system to deduce the appropriate amount of tip (MathWorks Inc, 2014a; p. '2-26')

This figure diagrammatically shows all of the Mamdani fuzzy inference system steps in order to deduce the disruption level of a given link within a 0 to 100 scale:

1. **Fuzzification of the input variables:** The first step is to take the inputs (i.e. crisp values in the range of 0 to 10) and determine the degree to which they belong to each of the corresponding fuzzy sets via the associated membership functions.

2. **Application of the fuzzy operator (AND or OR) in the antecedent:** Fuzzy sets and fuzzy operators can be thought as the *subjects* and *verbs* of fuzzy logic which consists of of "if-then" rules: a single fuzzy if-then rule assumes the conditional form "*if x is A then y is B". A* and *B* are linguistic values defined by fuzzy sets. The if-part of the rule "x is A" is called the *antecedent* or *premise*, while the then-part of the rule "y is B" is called the *consequent* or *conclusion*.

   Fuzzy logical operators such as AND & OR are applied to fuzzy values in the antecedent part. For example:

   antecedent **consequent**

   If 'accessibility degradation' is high AND time is sensitive then 'disruption to link' is high

   After the inputs are fuzzified (step 1), the degree to which each part of the antecedent is satisfied for each rule is known. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number is then applied to the output function. The input to the fuzzy operator is two or more membership values from fuzzified input variables, and the output is a single truth value (i.e. a number between 0 to 1). The most common type of method for the AND operator is the MIN method (which is used for the experimental tests of this study); and the most common type of method for the OR operator is the MAX method.

3. **Application of the *implication* method**: This stage involves assigning a weighting factor to each rule (default weighting is 1), and subsequently applying an *implication method* which can be one of the available standard implication methods such as *min* (minimum) which truncates the output fuzzy set, or *prod* (product) which scales the output fuzzy set (the former method is the most common type of implication method). The default *min* method has been used for the experimental tests of this study.

4. **Aggregation of the consequents across the rules:** Aggregation is the process whereby the outputs of the rules are combined, or *aggregated*, into a single fuzzy set. The input of the aggregation process is the list of truncated output functions returned by the implication process (step 3) for each rule. The output of the aggregation process is one fuzzy set for each output variable. MATLAB provides three built-in aggregation methods, including *max* (maximum), *probor* (probabilistic), and *sum* (simply the sum of each rule's output set). The default *max* method has been used for the experimental tests of this thesis.

5. **Defuzzification**: is the process of deducing a single output value from the aggregation results (the previous step). The most popular defuzzification method is reported to be the *centroid calculation*, which returns the centre of the area under the aggregate results curve.

Further information about these steps can be found in MATLAB fuzzy logic toolbox manual (MathWorks Inc., 2014a; pp. '2-22' to '2-27').

A.3 Alternative to the Mamdani Inference System procedures

A.3.1 Introduction to the Sugeno-type fuzzy inference

The Takagi-Sugeno-Kang, or in short Sugeno, method of fuzzy inference was introduced in 1985 (Sugeno, 1985), and is similar to Mamdani method in many respects. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant (MathWorks Inc., 2014a; pp. 2-91). A typical rule in Sugeno fuzzy model has the form:

If Input 1 = x and Input 2 = y, then Output is z = ax + by + c

For a zero-order Sugeno model, the output level z is a constant (a=b=0).

The output level $z_i$of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = x and Input 2 = y, the firing strength is:

w_i = AndMethod F x F y = (1( ), 2( ))

where $F_{1,2}$ (.) are the membership functions for Inputs 1 and 2.

The final output of the system is the weighted average of all rule outputs, computed as:

$$\text{Final Output} = \frac{\sum_{i=1}^{N} w_i \, z_i}{\sum_{i=1}^{N} w_i}$$

Where *N* is the number of rules. A Sugeno rule operates as shown in the following diagram:

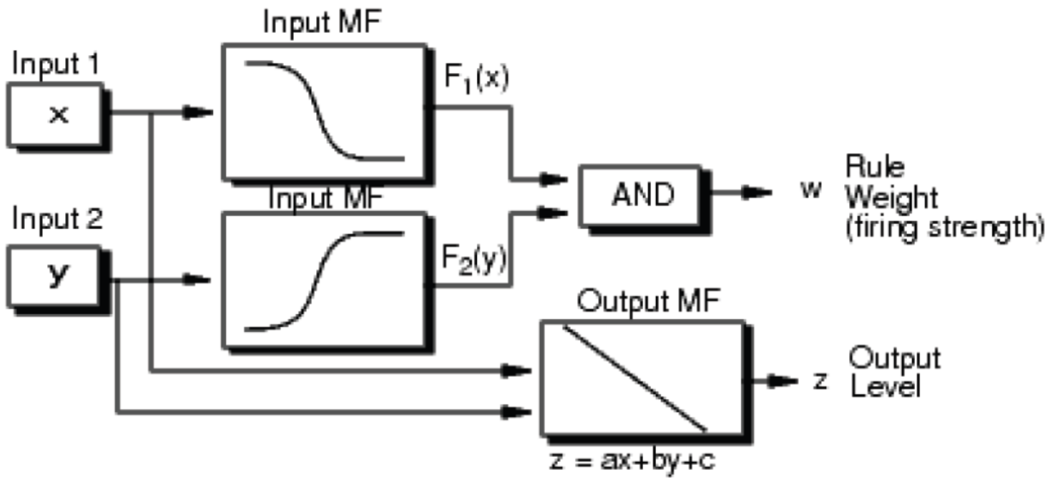


Figure A-6 Rule operation diagram for the Sugeno-type fuzzy inference system

A.3.2 Comparison of the Mamdani and Sugeno inference systems

Mamdani inference system has widespread acceptance, and is very intuitive and well-studied to human input. However because a Sugeno inference system is a more compact and computationally efficient representation than a Mamdani system, the Sugeno system lends itself better to the use of adaptive techniques for constructing fuzzy models. These adaptive techniques can be used to customize the membership functions so that the fuzzy system best models the data.

In brief, the Sugeno-type fuzzy inference system has the following advantages:

- It is computationally efficient.
- It works well with linear techniques (e.g., PID control).
- It works well with optimization and adaptive techniques.
- It has guaranteed continuity of the output surface.
- It is well suited to mathematical analysis.

Bibliography

New Roads and Street Works Act 1991. (c.22). London: Her Majesty's Stationery Office ('HMSO').

The Street Works (Fixed Penalty) (England) Regulations 2007 London: The Stationery Office Limited.

The Street Works (Registers, Notices, Directions and Designations) (England) Regulations 2007 London: The Stationery Office Limited.

Traffic Management Act 2004. (c.18). London: The Stationery Office Limited.

The National Joint Utility Group (NJUP). 2009. [Online]. [Accessed 9 February 2015]. Available from: www.njug.org.uk

Abbas, K.A. and Bell, M.G.H. 1994. System dynamics applicability to transportation modelling. *Transportation Research Part A.* **28**(5), pp.373-400.

Abdel-Aty, M.A. et al. 1995. Investigating effect of travel time variability on route choice using repeated-measurement stated preference data. *Transportation Research Record.* (1493), pp.39-45.

Agrawal, J. and Mathew, T.V. 2004. Transit route network design using parallel genetic algorithm. *Journal of Computing in Civil Engineering.* **18**(3), pp.248-256.

Ahmed, S. and Sahindis, N.V. 2003. An approximation scheme for stochastic integer programs arising in capacity expansion. *Operations Research.* **51**(3), pp.461-471.

Akiyama, T. et al. 1994. Traffic flow on urban networks with fuzzy information. *Memoirs of the Faculty of Engineering, Kyoto University.* **56**(2), pp.19-40.

Anchez-Silva, M.S. et al. 2005. A transport network reliability model for the efficient assignment of resources. *Transportation Research Part B.* **39**(1), pp.47-63.

Arora, J.S. 2004. *Introduction to Design Optimization.* 2nd ed. USA: Elsevier Academic Press.

Arora, S. and Barak, B. 2009. *Computational complexity: a modern approach.* USA: Cambridge University Press.

Ates, O. 2014. *A Decision Making Framework for Road User Cost Analysis along Freeway Work Zone Projects*. Ph.D thesis, Ohio University.

ATKINS. 2011. *DIADEM software.* [Online]. [Accessed 8 May 2014]. Available from: https://www.gov.uk/government/publications/diadem-software

Attoh-Okine, N.O. and Bowers, S. 2006. A Bayesian belief network model of bridge deterioration. *Proceedings of the Institution of Civil Engineers Bridge Engineering.* **159**(2), pp.69-76.

Austroads. 2007. *Process for Setting Intervention Criteria and Allocating Budgets : Literature Review.* [Online]. Austroads Publications. [Accessed 15 February 2015]. Available from: https://www.onlinepublications.austroads.com.au/items/AP-T80-07

Autroads. 2006. *Process for Setting Intervention Criteria and Allocating Budgets : Process Description and Application.* [Online]. Autroads Publications. [Accessed 15 February 2015]. Available from: https://www.onlinepublications.austroads.com.au/items/AP-T69-06

Awasthi, A. et al. 2011. A hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluating transportation service quality. *Computers & Industrial Engineering.* **61**(3), pp.637-646.

Ayed, A. et al. 2014. Development of a Decision Support Tool for Arterial Roads Rehabilitation in Hamilton. In: *2014 Annual Conference of the Transportation Association of Canada*, *Montreal, Canada*.

Balijepalli, C. and Oppong, O. 2014. Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography.* **39**, pp.145-155.

Ballijepalli, C. et al. 2004. *Advancing Methods for Evaluating Network Reliability.* [Online]. Leeds: Institute for Transport Studies (ITS). [Accessed 11 February 2015]. Available from: http://webarchive.nationalarchives.gov.uk/20070306100043/http:/www.dft.gov.uk/pgr/economics/rdg/jtv/amenr/advancingmethodsforevaluatin3080

Bao, Q. et al. 2012. Improved hierarchical fuzzy TOPSIS for road safety performance evaluation. *Knowledge-Based Systems.* **32**(1), pp.84-90.

Bar-Gera, H. 2002. Origin-based algorithm for the traffic assignment problem. *Transportation Science.* **36**(4), pp.398-417.

Bar-Gera, H. 2013. *Transportation Network Test Problems.* [Online]. [Accessed 11 February 2015]. Available from: http://www.bgu.ac.il/~bargera/tntp/

Batley, R. et al. 2008. *Multimodal Travel Time Variability (Final Report).* [Online]. Institute for Transport Studies (ITS). [Accessed 12 February 2015]. Available from: http://webarchive.nationalarchives.gov.uk/+/http:/www.dft.gov.uk/pgr/economics/rdg/jtv/finalreport.pdf

Beckmann, M. et al. 1956. *Studies in the Economics of Transportation.* New Haven Yale University Press.

Bell, M.G.H. and Iida, Y. 1997. *Transportation Network Analysis.* Chichester John Wiley & Sons.

Ben-Akiva et al. 1997. Simulation laboratory for evaluating dynamic traffic management systems. *Journal of Transportation Engineering* **123**(4), pp.283-289.

Ben-Akiva, M. and Bierlaire, M. 1997. Development of a route guidance generation system for real-time application. In: *Proceedings of the IFAC Transportation Systems 97 Conference*, *Chania*. pp.405-410.

Bergomi, M. 2009. *Traffic assignment problem: the stochastic user equilibrium*. Ph.D thesis, Swiss Federal Institute of Technology Zurïch.

Bourne, N. et al. 2008. *A Review of Literature on the Nature of the Impact of Roadworks on Traffic Movement and Delay - Published Project Report PPR 348.* [Online]. UK: TRL. [Accessed 13 February 2015]. Available from: http://www.trl.co.uk/reports-publications/trl-reports/transport-planning/report/?reportid=6364

Brennand, A.W. and Agency, N.Z.T. 2011. *Incorporating Travel Time Reliability in the Estimation of Assignment Models.* [Online]. Wellington: NZ Transport Agency,. [Accessed 14 December 2011]. Available from: http://www.nzta.govt.nz/resources/research/reports/464/docs/464.pdf

Britton, C. et al. 2003. *Street and Highway Works Research Study.* Surrey, England: AMTEC CONSULTING GROUP.

Brown, S. and Hutton, A. 2013. Developments in the Real-time Evaluation of Audience Behaviour at Planned Events. *International Journal of Event and Festival Management.* **4**(1), pp.43-55.

Buran, B. and Feyzioğlu, O. 2013. Considering sustainability in the planning of transit systems: Istanbul case. In: *19th Annual International Conference on Urban Transport and the Environment, 29-31 May 2013,*, *Kos, Greece*. Southampton: WIT Press, pp.423-434.

Bureau of Public Roads (BPR). 1964. *Traffic Assignment Manual.* Washington, D.C: U.S. Department of Commerce, Urban Planning Division.

Byon, Y. 2011. *GISTMARG: GPS and GIS for Traffic Monitoring and Route Guidance*. Ph.D thesis, University of Toronto.

Caggiani, L. et al. 2012. A metaheuristic dynamic traffic assignment model for OD matrix estimation using aggregate data. *Procedia - Social and Behavioral Sciences.* **54**(2012), pp.685--695.

Carey, M. et al. 2003. A Whole-Link Travel Time Model with Desirable Properties. *Transportation Science.* **37**(1), pp.83-96.

Chen, A. et al. 2010. Stochastic multi-objective models for network design problem. *Expert Systems with Applications.* **37**(2), pp.1608-1619.

Chen, A. and Subprasom, K. 2007. Analysis of regulation and policy of private toll roads in a build-operate-transfer scheme under demand uncertainty. *Transportation Research: Part A Policy and Practice.* **41**(6), pp.537-558.

Chen, A. et al. 2003. Mean-variance model for the build-operate-transfer scheme under demand uncertainty. *Transportation Research Record: Journal of the Transportation Research Board.* **1857**(1), pp.93-101.

Chen, A. et al. 2002. Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B: Methodological.* **36**(3), pp.225-252.

Chen, A. et al. 2011. Transport Network Design Problem under Uncertainty: A Review and New Developments. *Transport Reviews.* **31**(6), pp.743-768.

Chen, B.Y. et al. 2012. Vulnerability analysis for large-scale and congested road networks with demand uncertainty. *Transportation Research Part A: Policy and Practice.* **46**(3), pp.501-516.

Chen, B.Y. et al. 2012. Vulnerability analysis for large-scale and congested road networks with demand uncertainty. *Transportation Research Part A: Policy and Practice.* **46**(3), pp.501-516.

Chen, B.Y. et al. 2011. An efficient solution algorithm for solving multi-class reliability-based traffic assignment problem. *Mathematical and Computer Modelling.* **54**, pp.1428-1439.

Chen, B.Y. et al. 2011. An efficient solution algorithm for solving multi-class reliability-based traffic assignment problem. *Mathematical and Computer Modelling.* **54**(5), pp.1428-1439.

Chen, Y. and Huang, C. 2013. Trust Region Method for Network Design Problem with Equilibrium Constrains. *Information Technology Journal.* **12**(20).

Cheng, Y. et al. 2012. Enhanced analysis of work zone safety through integration of statewide crash and lane closure system data. *Transportation Research Record: Journal of the Transportation Research Board.* **2291**(1), pp.17-25.

Cheu, R. et al. 2007. *Strategies for Improving Travel Time Reliability.* Texas Department of Transportation.

Cheung, B.K.S. et al. 2008. Dynamic routing model and solution methods for fleet management with mobile technologies. *International Journal of Production Economics.* **113**(2), pp.694-705.

Chien, S. and Tang, Y. 2012. Scheduling highway work zones with genetic algorithm considering the impact of traffic diversion. *Journal of Advanced Transportation.* **48**(4), pp.287-303.

Chiou, S. 2008. A hybrid approach for optimal design of signalized road network. *Applied Mathematical Modelling.* **32**(2), pp.195-207.

Chiu, Y. et al. 2011. *Dynamic traffic assignment: A primer.* [Online]. Transportation Research Board (TRB). [Accessed 16 March 2014]. Available from: http://onlinepubs.trb.org/onlinepubs/circulars/ec153.pdf

Choudhury, C.F. et al. 2011. Evaluating the Impact of Interventions on Network Capacity. In: *Proceedings of the 90th Annual Meeting of the Transportation Research Board*.

Chu, D. et al. 2013. Assessment system construction for cooperative vehicle infrastructure system based on fuzzy analytic hierarchy process. In: *Proceedings of the 2nd International Conference on Transportation Information and Safety, Wuhan, China*. pp.91-100.

Clark, A. 2006. *Optimal Congestion Pricing Schemes Including Heterogeneous Users and Time of Day Variability- PhD Upgrade Report.* Institute for Transport Studies (ITS).

Clark, S.D. and Watling, D.P. 2007. Sensitivity analysis of the variable demand probit stochastic user equilibrium with multiple user-classes. *Transportation Research Part B: Methodological.* **41**(6), pp.593-615.

Clark, S.W. and Watling, D.P. 2005. Modelling Network Travel Time Reliability Under Stochastic Demand. *Transportation Research. Part B: Methodological.* **39**(2), pp.119-40.

Coello, C. and Artemio, C. 2012. Constraint-handling techniques used with evolutionary algorithms. In: *Proceedings of the 14th annual conference companion on genetic and evolutionary computation New York*. ACM Press, pp.849-872.

Cohen, L. et al. 2011. *Research Methods in Education.* 7th ed. Oxon, UK: Routledge.

Connors, R. et al. 2009. Evaluation and Design of Transport Network Capacity Under Demand Uncertainty. *Transportation Research Record: Journal of the Transportation Research Board.* **2090**(1), pp.17-28.

Connors, R. et al. 2005. Equitable Network Design. *Journal of the Eastern Asia Society for Transportation Studies.* **6**, pp.1382-1397.

Consortiumof stakeholders. 2013. *Local Transport Planning Network.* [Online]. Available from: http://www.ltpnetwork.gov.uk/

Cumberbatch, S. 2005. What lies beneath. *SURVEYOR.* pp.14-15.

Curtin, K. and Biba, S. 2011. The transit route arc-node service maximization problem. *European Journal of Operational Research.* **208**(1), pp.46-56.

Daellenbach, H.G. 1997. *Systems and Decision Making: a management science approach.* Chichester: Wiley.

Daganzo, C. 1995. Properties of link travel time functions under dynamic loads. *Transportation Research Part B: Methodological.* **29**(2), pp.95-98.

Dantzig, G. and Harvey, R. 1979. Formulating and solving the network design problem by decomposition. *Transportation Research Part B: Methodological.* **13**(1), pp.5-17.

DAT.Mobility. 2014. *OmniTRANS Product Overview.* [Online]. [Accessed 3 May 2014]. Available from: http://www.omnitrans-international.com/en/products/omnitrans/product-overview

De, P. et al. 1997. Complexity of the discrete time-cost tradeoff problem for project networks. *Operations research.* **45**(2), pp.302-306.

Deĭneko, V. and Woeginger, G. 2001. Hardness of approximation of the discrete time-cost tradeoff problem. *Operations Research Letters.* **29**(5), pp.207-210.

Department for Transport. 2006. *Practical Guide to Street Works.* [Online]. London: TSO. [Accessed 22 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4382/practicalguidetostreetworks.pdf

Department for Transport. 2001. *Frameworks for Modelling the Variability of Journey Times on the Highway Network - Part C Urban Journey Time Variability.* [Online]. [Accessed 12 November 2009]. Available from: http://www.dft.gov.uk/pgr/economics/rdg/ttv/backgroundstudies/highwayjourneytimes/frameworksformodellingthevar3081

Department for Transport. 2003. *Safety at Street Works and Road Works A Code of Practice.* [Online]. Great Britain: Department for Transport. [Accessed 20 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/321056/safety-at-streetworks.pdf

Department for Transport. 2004a. *Technical Guidance on Accessibility Planning in Local Transport Plans.* [Online]. Great Britain: Department for Transport. [Accessed 20 May 2010]. Available from: http://assets.dft.gov.uk/publications/accessibility-planning-guidance/accessibility-planning-guidance-full-guidance.pdf

Department for Transport. 2004b. *Traffic Management Act 2004 Network Management Duty Guidance.* [Online]. Department for Transport. [Accessed 1 February 2015]. Available from: http://webarchive.nationalarchives.gov.uk/+/http:/www.dft.gov.uk/pgr/roads/tpm/tmaportal/tmafeatures/tmapart2/tmafeaturespart2.pdf

Department for Transport. 2007. *Working Together: A Good Practice Guide to Managing Works in the Street.* [Online]. London: TSO. [Accessed 20 February 2015]. Available from: http://www.hauc-uk.org.uk/uploads/best_practice.pdf

Department for Transport. 2008. *Traffic Management Act 2004 Code of Practice for Permits.* [Online]. Department for Transport. [Accessed 20 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/49521/pdfpermitscop.pdf

Department for Transport. 2009a. *DMRB Vol 13: Economic Assessment of Road Schemes - COBA (COst Benefit Analysis) Manual.* [Online]. London: The Stationary Office. [Accessed 7 May 2010].

Department for Transport. 2009b. *Modelling and appraisal of journey time variability - interim report.* [Online]. [Accessed 1 February 2010]. Available from: http://www.dft.gov.uk/pgr/economics/rdg/ttv/backgroundstudies/interimreport/

Department for Transport. 2009c. *Street Works.* [Online]. [Accessed 15 January 2009]. Available from: http://www.dft.gov.uk/pgr/roads/network/local/streetworks/

Department for Transport. 2009d. *TAG Unit 3.5.6 The Economy Objective Values of Time and Operating Costs* [Online]. [Accessed 5 December 2009]. Available from: http://www.dft.gov.uk/webtag/documents/expert/pdf/unit3.5.6.pdf

Department for Transport. 2009e. *TAG Unit 3.5.7 The Reliability Sub-Objective.* [Online]. [Accessed 5 December 2009]. Available from: http://www.dft.gov.uk/webtag/documents/expert/pdf/unit3.5.7.pdf

Department for Transport. 2009f. *Traffic Signs Manual - Chapter 8: Traffic Safety Measures and Signs for Road Works and Temporary Situations (Part 1 and 2).* [Online]. 2nd ed. London: TSO. [Accessed 7 September 2011]. Available from: https://www.gov.uk/government/publications/traffic-signs-manual

Department for Transport. 2011. *Lane Rental Schemes in England Consultation.* [Online]. London: Department for Transport. [Accessed 22 November 2014]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/2587/consultationdocument.pdf

Department for Transport. 2012a. *Accessibility Sub-objective.* [Online]. [Accessed 1 March 2012]. Available from: http://www.dft.gov.uk/webtag/topics/index.php

Department for Transport. 2012b. *Lane Rental Schemes: Guidance to English Local Highway Authorities.* [Online]. London: Department for Transport. [Accessed 5 January 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/3741/guidance.pdf

Department for Transport. 2012c. *New Roads and Street Works Act 1991 Code of Practice for the Co-ordination of Street Works and Works for Road Purposes and Related Matters* [Online]. London: The Stationary Office. [Accessed 12 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/43578/street-works-code-of-practice.pdf

Department for Transport. 2012d. *TAG Unit 3.5.6 Values of Time and Vehicle Operating Costs.* [Online]. [Accessed 22 February 2015]. Available from: http://www.dft.gov.uk/webtag/documents/expert/pdf/u3_5_6-vot-op-cost-120723.pdf

Department for Transport. 2014a. *Traffic Counts.* [Online]. [Accessed 22 August 2008]. Available from: http://www.dft.gov.uk/traffic-counts/

Department for Transport. 2014b. *Transport Analysis Guidance - Guidance for the Senior Responsible Officer.* [Online]. [Accessed 25 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/370499/tag-guidance-for-senior-responsible-officer.pdf

Department for Transport. 2014c. *Transport Analysis Guidance: WebTAG.* [Online]. [Accessed 20 February 2015]. Available from: https://www.gov.uk/transport-analysis-guidance-webtag

Department for Transport . 2014d. *DMRB Vol 14: QUeues and Dealays at ROadworks (QUADRO).* [Online]. [Accessed 9 February 2015]. Available from: https://www.trlsoftware.co.uk/products/economic_appraisal/quadro

Department of the Environment Transport and the Regions. 2001. *Best practice in street works and highway works.* [Online]. London: The Stationary Office. [Accessed 10 April 2014]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4383/bestpracticeinstreetworks.pdf

Dial, R.B. 2006. A path-based user-equilibrium traffic assignment algorithm that obviates path storage and enumeration. *Transportation Research Part B: Methodological.* **40**(10), pp.917-936.

Digital National Framework Consortium. 2009. *Digital National Framework (DNF).* [Online]. [Accessed 9 February 2015]. Available from: www.dnf.org

Ding, Y. and Lisnianski, A. 2008. Fuzzy universal generating functions for multi-state system reliability assessment. *Fuzzy Sets and Systems.* **159**(3), pp.307-324.

DNF Project Consortium. 2011. *About Digital National Framework (DNF).* [Online]. [Accessed 6 June 2014]. Available from: http://www.dnf.org/about_DNF/

Dorigo, M. 1992. *Optimization, learning and natural algorithms*. Ph.D thesis, Politecnico di Milano.

Ehrgott, M. et al. 2010. *Multiple criteria decision making for sustainable energy and transportation systems: proceedings of the 19th International Conference on Multiple Criteria Decision Making, Auckland, New Zealand, 7th-12th January 2008.* Springer Science & Business Media.

ELGN.org. 2013. *roadworks.org.* [Online]. [Accessed 15 March 2013]. Available from: http://roadworks.org/

El-Rashidy, R.A. and Grant-Muller, S.M. 2014. An assessment method for highway network vulnerability. *Journal of Transport Geography.* **34**, pp.34-43.

Erath, A. and Birdsall, J. 2009. Vulnerability assessment methodology for Swiss road network. *Transportation Research Record: Journal of the Transportation Research Board.* **2137**(1), pp.118-126.

European Commission. 2014. *About INSPIRE (Infrastructure for Spatial Information in the European Community).* [Online]. [Accessed 5 June 2014]. Available from: http://inspire.ec.europa.eu/index.cfm/pageid/48

Farahani, R. and Miandoabchi, E. 2013. A review of urban transportation network design problems. *European Journal of Operational Research.* **229**(2), pp.281-302.

Federal Highways Administration (FHWA). 2014. *DYNAMSMART -P.* [Online]. [Accessed 24 October 2014]. Available from: http://www.fhwa.dot.gov/research/deployment/dynasmart.cfm

Feng, T. et al. 2009. Comparison of transportation network optimization with different equity measures using bilevel programming approach. In: *Transportation Research Board 88th Annual Meeting*.

Floudas, C. 1999. *Handbook of test problems in local and global optimization.* [Online]. Springer. [Accessed 10 February 2014]. Available from: http://www.springer.com/gp/book/9780792358015

Flyvbjerg, B. et al. 2005. How (in) accurate are demand forecasts in public works projects?: The case of transportation. *Journal of the American Planning Association.* **71**(2), pp.131-146.

Frank, M. and Wolfe, P. 1956. An algorithm for quadratic programming. *Naval research logistics quarterly.* **3**(1-2), pp.95-110.

Friesz, T. 1985. Transportation network equilibrium, design and aggregation: key developments and research opportunities. *Transportation Research Part A: General.* **19**(5), pp.413-427.

Friesz, T. et al. 1993. A variational inequality formulation of the dynamic network user equilibrium problem. *Operations Research.* **41**(1), pp.179-191.

Friesz, T.L. et al. 1993. A variational inequality formulation of the dynamic network user equilibrium problem. *European Journal of Operational Research.* **41**(1), pp.179-191.

Furda, D. and Saffarian, B.B. 2012. *Work Zone's Capacity Estimation and Investigation of Potential of Dynamic Merge Systems*. MSc thesis, Linköping University.

Gallo, M. et al. 2010. A meta-heuristic approach for solving the urban network design problem. *European Journal of Operational Research* **201**(1), pp.144-157.

Gao, H. and Zhang, X. 2013. A Markov-Based Road Maintenance Optimization Model Considering User Costs. *Computer-Aided Civil and Infrastructure Engineering.* **28**(6), pp.451-464.

Gao, Z. et al. 2007. A globally convergent algorithm for transportation continuous network design problem. *Optimization and Engineering.* **8**(3), pp.241-257.

Gao, Z. et al. 2005. Solution algorithm for the bi-level discrete network design problem. *Transportation Research Part B: Methodological.* **39**(6), pp.479-495.

Gartner, N. 1980. Optimal traffic assignment with elastic demands: A review part I. Analysis framework. *Transportation Science.* **14**(2), pp.174-191.

Gartner, N. 1980. Optimal traffic assignment with elastic demands: A review part II. algorithmic approaches. *Transportation Science.* **14**(2), pp.192-208.

Gemar, M.D. 2013. *Subnetwork analysis for dynamic traffic assignment: methodology and application*. Ph.D thesis, The University of Texas at Austin.

Gentile, G. 2014. Local User Cost Equilibrium: a bush-based algorithm for traffic assignment. *Transportmetrica A: Transport Science.* **10**(1), pp.15-54.

Georgiou, G.N. 1995. *Modelling the Day-To-Day Dynamics of Route Choice*. MSc thesis, University of Leeds.

Ghataee, M. and Hashemi, S. 2009. Traffic assignment model with fuzzy level of travel demand: An efficient algorithm based on quasi-Logit formulas. *European Journal of Operational Research.* **194**(2), pp.432-451.

Ghataee, M. and Hashemi, S.M. 2009. Application of fuzzy minimum cost flow problems to network design under uncertainty. *Fuzzy Sets and Systems.* **160**(22), pp.3263-3289.

Goetz, A. and Szyliowicz, J. 1997. Revisiting transportation planning and decision making theory: The case of Denver International Airport. *Transportation Research Part A: Policy and Practice.* **31**(4), pp.263-280.

Goldberg, D.E. 1989. *Genetic algorithms in search, optimization, and machine learning.* Boston, USA: Addison-wesley.

Goodwin, P. 2005. *Utilities' street works and the cost of traffic congestion.* [Online]. [Accessed 5 March 2014]. Available from: http://www.njug.org.uk/wp-content/uploads/93.pdf

Goodwin, P. et al. 1998. Evidence of a wide range of responses to capacity reducttiion:. *Traffic Engineering and Control.* **3**, pp.348-354.

Gransberg, D.D. et al. 2006. *Construction equipment management for engineers, estimators, and owners.* Boca Raton: CRC Press.

Gu, W. et al. 2012. Joint optimization of pavement maintenance and resurfacing planning. *Transportation Research Part B: Methodological.* **46**(4), pp.511-519.

Hahn, B.H. and Valentine, D.T. 2009. *Essential Matlab for Engineers and Scientists.* 4th ed. London: Academic Press.

Halden, D. et al. 2005. *Accessibility Analysis Literature Review* [Online]. Available from: home.wmin.ac.uk/.../SAMP_WP3_Accessibility_Modelling.pdf

Hanss, M. 2005. *Applied fuzzy arithmetic An Introduction with Engineering Applications.* Berlin: Springer.

He, K. 2012. *A behaviour study of transport impacts of mega events*. Ph.D thesis, University of Southampton.

He, L. et al. 2014. An optimization model of the layout of public bike rental stations based on B+R mode. In: Wong, W.E. and Zhu, T. eds. *Computer*

Engineering and Networking: Proceedings of the 2013 International Conference on Computer Engineering (CENet2013). London: Springer International Publishing, pp.1341-1348.

Hearn, D.W. and Yildirim, M.B. 2002. A toll pricing framework for traffic assignment problems with elastic demand. In: Hearn, D. and Yildirim, M. eds. *Transportation and Network Analysis: Current Trends Applied Optimization* Springer US, pp.135-145.

Hegazy, T. and Peztold, K. 2003. Genetic Optimization for Dynamic Project Control. *Journal of Construction Engineering and Management.* **129**(4), pp.396-404.

Highways Agency. 2009. *The Journey Time Reliability Toolkit.* [Online]. [Accessed 5 September 2009]. Available from: http://www.highways.gov.uk/specialist-information/highways-agency-toolkits/the-journey-time-reliability-toolkit/

Highways Agency. 2009. *Value Management of the Regional Roads Programme.* [Online]. [Accessed 5 November 2009]. Available from: http://www.highways.gov.uk/specialist-information/highways-agency-toolkits/the-journey-time-reliability-toolkit/

Highways Magazine. *Utility companies could face roadworks fines in Kent.* [Online]. [Accessed 17 February]. Available from: http://highwaysmagazine.co.uk/utility-companies-could-face-roadworks-fines-in-kent/

Highways Magazine. 2008. Software keeps traffic moving.

Highways Magazine. 2009. Traffic flow system saves months. *Highways Magazine.* **78**, pp.32-33.

Highways Magazine. 2014. *Councils and utility companies sign street works pledge.* [Online]. [Accessed 13 February 2014]. Available from: http://www.highwaysmagazine.co.uk/councils-and-utility-companies-sign-street-works-pledge-20140213

Hindelang, T.J. and Muth, J.F. 1979. A dynamic programming algorithm for decision CPM networks. *Operations Research.* **27**(2), pp.225-241.

HM Treasury. 2014. *The Green Book: appraisal and evaluation in central governmen.* [Online]. London: TSO. [Accessed 22 February 2015]. Available from: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

Hsu, H.P. 2010. *Schaum's Outline of Probability, Random Variables, and Random Processes.* 2nd ed. New York: McGraw-Hill.

Huang, H. and Yang, H. 2004. The multi-class, multi-criteria traffic network equilibrium and systems optimum problem. *Transportation Research Part B.* **38**(1), pp.1-15.

Hurink, J. and Knust, S. 2005. Tabu search algorithms for job-shop problems with a single transport robot. *European journal of operational research.* **162**(1), pp.99-111.

Husdal, J. 2006. *Transport Network Vulnerability - which matrics should we use?* [Online]. [Accessed 10 February 2015]. Available from: http://www.husdal.com/2006/05/16/transport-network-vulnerability-which-metrics-should-we-use/

INRO Software. 2015. *EMME transportation forecasting software.* [Online]. [Accessed 1 February 2015]. Available from: http://www.inrosoftware.com/en/

Institution of Civil Engineers. 2011. SPOTLIGHT: UTILITY MAPPING. *New Civil Engineer.* **16.06.11**, pp.30-34.

Inuiguchi, M. and Ramík, J. 2000. Possibilistic linear programming: a brief review of fuzzy mathematical programming and a comparison with stochastic programming in portfolio selection problem. *Fuzzy sets and systems.* **111**(1), pp.3-28.

Iowa Department of Transportation. 2014. *Effectiveness of Work Zone Intelligent Transportation Systems.* [Online]. Columbia, USA: University of Missouri. [Accessed 22 February 20145]. Available from: http://publications.iowa.gov/15989/1/IADOT_InTrans_TPF-5%28081%29_work-zone_ITS_effectiveness.pdf

Jabalameli, M. et al. 2011. An efficient algorithm to solve dynamic budget constrained uncapacitated facility location-network design problem. *International Journal of Business and Management Studies.* **3**(1), pp.263-273.

JabalAmeli, M.S. and Mortezaei, M. 2011. A hybrid model for multi-objective capacitated facility location network design problem. *International Journal of Industrial Engineering Computations.* **2**(3), pp.509-524.

Jenelius, E. et al. 2006. Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice.* **40**(7), pp.537-560.

Jing, X. et al. 2012. A Hybrid Genetic Algorithm for Route Optimization in Multimodal Transport. In: *Fifth International Symposium on Computational Intelligence and Design (ISCID)*, *28-29 October 2012, Hangzhou*. IEEE, pp.261-264.

Kalić, M. and Teodorović, D. 2003. Trip distribution modelling using fuzzy logic and a genetic algorithm. *Transportation Planning and Technology.* **26**(3), pp.213-238.

Kandil, A. et al. 2010. Optimization of highway construction work zones: the agency and user cost tradeoff. In: *Proceedings of the International Conference on Computing in Civil and Building Engineering (icccbe 2010), Nottingham*. Nottingham University Press, p.255.

Karshanas, S. and Haber, D. 1990. Economic optimization of construction project scheduling. *Construction Management and Economics.* **8**(2), pp.135-146.

Khurshid, M.B. et al. 2015. A framework for assessing the consequences of deferred or hastened highway asset interventions. *Structure and Infrastructure Engineering.* **11**(3), pp.1-15.

Kilby, K. and Smith, N. 2012. *Accessibility Planning Policy: Evaluation and Future Direction* [Online]. [Accessed 16 February 2015]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/3190/accessibility-planning-evaluation-report.pdf

Kim, B.J. et al. 2009. Sequencing and scheduling highway network expansion using a discrete network design model. *The Annals of Regional Science.* **42**(3), pp.621-642.

Kittelson & Associates Inc. *Evaluating Alternative Operations Strategies to Improve Travel Time Reliability.* [Online]. Transportation Research Board (TRB). [Accessed 12 February 2015]. Available from: http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-L11-RR-1.pdf

Knoop, V. and Snelder, M. 2012. Link-level vulnerability indicators for real-world networks. *Transportation Research Part A: Policy and Practice* **46**(5), pp.843-854.

Koh, A. 2007. Solving transportation bi-level programs with differential evolution. In: *IEEE Congress on Evolutionary Computation (CEC 2007)*, *25-28 September 2007, Singapore*. IEEE, pp.2243-2250.

Koh, A. 2011. Cooperative and non cooperative models of toll competition between cities. In: *ITS (of Leeds University) Internal Seminar*, *23 September 2011, University of Leeds*.

Kreyszig, E. 2011. *Advanced Engineering Mathematics.* 10th ed. Singapore: John Wiley & Sons.

Lam, W. and Huang, H. 1992. A combined trip distribution and assignment model for multiple user classes. *Transportation Research Part B: Methodological.* **26**(4), pp.275-287.

Lam, W.H.K. et al. 2008. Modeling impacts of adverse weather conditions on a road network with uncertainties in demand and supply. *Transportation Research Part B: Methodological.* **42**(10), pp.890-910.

Le, K.V. and Li, O.K. 1989. Modeling and Analysis of Systems with Multimode Components and Dependent Failures. *IEEE Transactions on Reliability.* **38**(1), pp.68-75.

LeBlanc, L. et al. 1975. An efficient approach to solving the road network equilibrium traffic assignment problem. *Transportation Research.* **9**(5), pp.309-318.

Lee, H.-Y. 2014. Planning work crew assignments for pedestrian area renovation to improve its impact on the public. *Journal of Civil Engineering and Management.* **20**(3), pp.338-349.

Leung, J. ed. 2004. *Handbook of Scheduling: Algorithms, Models, and Performance Analysis* USA: Chapman & Hall/CRC.

Lewis, M. and Woldesenbet, A. 2013. *Data and Information Integration Framework for Highway Project Decision Making.* [Online]. Oklahoma Transportation Center [Accessed 22 February 2015]. Available from: http://www.oktc.org/otc/files/finalReports/OTCREOS11.1-30-F.pdf

Li, J. and Yang, S.W. 2013. Study on quality evaluation system for arterial highways based on fuzzy comprehensive evaluation. *Applied Mechanics and Materials.* **438**, pp.1952-1957.

Li, J. and Zhang, X. 2013. AHP-based safety risk assessment and specialized design of a metro tunnel near a highway bridge. *Modern Tunnelling Technology.* **2013**(6), pp.152-157.

Li, R. 2004. *Examining travel time variability using AVI data.* [Online]. The University of Sydney and Monash University. [Accessed 16 February 2015]. Available from: http://eng.monash.edu.au/civil/assets/document/research/centres/its/publications/its-wp-04-23.pdf

Li, S. 1996. New approach for optimization of overall construction schedule. *Journal of construction engineering and management.* **122**(1), pp.7-13.

Li, Y. and Madanat, S. 2002. A steady-state solution for the optimal pavement resurfacing problem. *Transportation Research Part A: Policy and Practice.* **36**(6), pp.525-535.

Lighthill, M. and Whitham, G. 1955. On kinematic waves. I. Flood movement in long rivers. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences.* **229**, pp.281-316.

Lisnianski, A. and Levitin, G. 2003. *Multi-state System Reliability Assessment, Optimization, Applications.* London: World Scientific Publishing.

Liu, B. 2009. *Theory and Practice of Uncertain Programming.* London: Springer.

Lo, H.K. et al. 2006. Degradable transport network: Travel time budget of travelers with heterogeneous risk aversion. *Transportation Research Part B: Methodological.* **40**(9), pp.792-806.

Lomax, T. et al. 2003. *Selecting Travel Time Reliability Measures* [Online]. [Accessed 16 February 2015]. Available from: http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/TTI-2003-3.pdf

London Evening Standard. 2010. *More misery on London roads as potholes toll soars to 121,000.* [Online]. [Accessed 25 March 2010]. Available from: http://www.standard.co.uk/news/more-misery-on-london-roads-as-potholes-toll-hits-121000-6729196.html

Long, J. et al. 2010. A turning restriction design problem in urban road networks. *European Journal of Operational Research* **206**(3), pp.569-578.

Lukas, K. and Borrmann, A. 2011. Minimizing the traffic impact caused by infrastructure maintenance using ant colony optimization. In: *the 28th International Conference on Automation and Robotics in Construction*, *Seoul, Korea*.

Luke, S. 2009. *Essentials of Metaheuristics.* [Online]. George Mason University. [Accessed 16 February 2015]. Available from: http://www.cs.put.poznan.pl/mkomosinski/materialy/optymalizacja/extras/Essentials.pdf

Magnanti, T. and Wong, R. 1984. Network design and transportation planning: Models and algorithms. *Transportation Science.* **18**(1), pp.1-55.

Mamdani, E.H. and Assilian, S. 1975. An experiment in linguistic synthesis with a fuzzy logic controller. *International journal of man-machine studies.* **7**(1), pp.1-13.

Mapping the Underworld Project Consortium. 2009. *Mapping the Underworld.* [Online]. [Accessed 5 June 2014]. Available from: http://www.mappingtheunderworld.ac.uk/

Margiotta, R. 2002. Travel time reliability its measurement and improvement. In: *9th World Congress on ITS*. Cambridge Systematics Inc.

Marsden, G. et al. 2014. *Disruption - unlocking low carbon travel.* [Online]. [Accessed 28 January 2014]. Available from: http://www.disruptionproject.net/

MathWorks Inc. 2014a. *(MATLAB) Fuzzy Logic Toolbox User's Guide (R2014b).* [Online]. MathWorks Inc. [Accessed 10 February 2015]. Available from: http://www.mathworks.co.uk/help/pdf_doc/fuzzy/fuzzy.pdf

MathWorks Inc. 2014b. *(MATLAB) Global Optimization Toolbox User's Guide (R2014b).* [Online]. MathWorks Inc. [Accessed 9 February 2015]. Available from: http://www.mathworks.co.uk/help/pdf_doc/gads/gads_tb.pdf

MathWorks Inc. 2014c. *Hybrid Scheme in the Genetic Algorithm.* [Online]. [Accessed 7 November 2014]. Available from: http://www.mathworks.co.uk/help/gads/examples/hybrid-scheme-in-the-genetic-algorithm.html

MathWorks Inc. 2014d. *MATLAB The language of Technical Computing.* [Online]. [Accessed 20 April 2014]. Available from: http://www.mathworks.co.uk/products/matlab/

MathWorks Inc. 2014e. *(MATLAB) Optimization Toolbox User's Guide.* [Online]. MathWorks Inc,. [Accessed 12 February 2015]. Available from: http://uk.mathworks.com/help/pdf_doc/optim/optim_tb.pdf

May, A. 1990. *Traffic flow fundamentals.* New Jersey: Prentice-Hall.

McMohan, J. 2007. *Solution to Sports Scheduling Problem using Constraint Programming*. MSc thesis, University of Leeds.

McNiff, J. 2002. *Action Research for Professional Development: Concise Advice for New Action Researchers* [Online]. 3rd ed. [Accessed 16 February 2015]. Available from: http://www.jeanmcniff.com/userfiles/file/Publications/AR%20Booklet.doc

Melkote, S. and Daskin, M.S. 2001. Capacitated facility location/network design problems. *European Journal of Operational Research.* **129**(3), pp.481-495.

Meng, Q. and Weng, J. 2013. Optimal subwork zone operational strategy for short-term work zone projects in four-lane two-way freeways. *Journal of Advanced Transportation.* **47**(2), pp.151-169.

Miandoabchi, E. and Farahani, R. 2011. Optimizing reserve capacity of urban road networks in a discrete Network Design Problem. *Advances in Engineering Software.* **42**(12), pp.1041-1050.

Miandoabchi, E. and Farahani, R. 2012. Hybrid evolutionary metaheuristics for concurrent multi-objective design of urban road and public transit networks. *Networks and Spatial Economics.* **12**(3), pp.441-480.

Minhans, A. 2013. Measurement of effectiveness and difficulty of traffic management measures in disasters. *Jurnal Teknologi* **65**(3), pp.41-51.

Mishra, S. et al. 2013. Multi-entity perspective transportation infrastructure investment decision making. *Transport Policy.* **30**(2013), pp.1-12.

Mohaymany, A. 2012. A Reliability-Based Resource Allocation Model for Transportation Networks Affected by Natural Disasters. *PROMET-Traffic&Transportation* **24**(6).

Moreno-Quintero, E. 2004. *Planner-User Interactions in Road Freight Transport - A Modelling Approach with a Case Study from Mexico*. Ph.D thesis, University of Leeds.

Morlok, E. and Chang, D.J. 2004. Measuring capacity flexibility of a transportation system. *Transportation Research Part A.* **38**(6), pp.405-420.

Morris, J. et al. 1979. Accessibility indicators for transport planning. *Transportation Research Part A: General.* **13**(2), pp.91-109.

Mundhe, S. and Dongre, M. 2014. Intelligent Communication Pattern for Effective Congestion Control in VANET. *International Journal of Current Engineering and Technology.* **4**(4).

Murray-Tuite, P. and Mahmassani, H. 2004. Methodology for determining vulnerable links in a transportation network. *Transportation Research Record: Journal of the Transportation Research Board* **1882**(1), pp.88-96.

National Joint Utility Group (NJUG). 2008. *NJUG Case Study No 4: Continuous Improvement for Street Works.* [Online]. [Accessed 9 February 2015]. Available from: http://www.njug.org.uk/wp-content/uploads/4_-_Continuous_Improvement_for_Street_Works.pdf

National Joint Utility Group (NJUG). 2013. *Volume 6 NJUG Guidelines on Co-ordination, Co-operation & Communication.* [Online]. [Accessed 9 February 2015]. Available from: http://www.njug.org.uk/volume-6-njug-guidelines-on-co-ordination-co-operation-communication%EF%BB%BF/

Ng, M. 2012. Traffic Flow Theory–Based Stochastic Optimization Model for Work Zones on Two-Lane Highways. *Journal of Transportation Engineering.* **138**(10), pp.1269-1273.

Ng, M. and Waller, S.T. 2010. A computationally efficient methodology to characterize travel time reliability using the fast Fourier transform. *Transportation Research Part B: Methodological.* **44**(10), pp.1202-1219.

Ning, F. et al. 2013. A study on driving behavior risk assessment method with multi-sensor information. In: *Second International Conference on Transportation Information and Safety (ICTIS 2013)*, *29 June - 2 July 2013, Wuhan, China*. ASCE Publications, pp.1428-1433.

Noland, R.B. and Polak, J. 2002. Travel time variability: a review of theoretical and empirical issues. *Transport Reviews.* **22**(1), pp.39-54.

Oh, J. et al. 2011. Bi-objective network optimization for spatial and temporal coordination of multiple highway construction projects. *KSCE Journal of Civil Engineering.* **15**(8), pp.1449-1555.

Ortuzar, J.d.D. and Willumsen, L. 2011. *Modelling transport.* 4th ed. UK: John Willey & Sons

Osyczka, A. 2002. *Evolutionary algorithms for single and multicriteria design optimization.* New York: Physica-Verlag.

Ouyang, Y. and Madanat, S. 2006. An analytical solution for the finite-horizon pavement resurfacing planning problem. *Transportation Research Part B: Methodological.* **40**(9), pp.767-778.

Pareto, V. and Politica, M.d.E. 1971. *Societa Editrice Libraria, Milano, Italy, 1906. Translated into English by AS Schwier as Manual of Political Economy.*

Parker, J. 2008. Briefing: The real cost of street works. *Proceedings of the Institution of Civil Engineers: Transport.* **161**(4), pp.175-176.

Patil, G. and Ukkusuri, S. 2007. Flexible design of transportation networks. In: *Proceedings of the 86th Annual Meeting of the Transportation Research Board, 21-25 January 2007, Washington D.C.*: TRB Publications.

Patil, G. and Ukkusuri, S.V. 2009. Multi-period transportation network design under demand uncertainty. *Transportation Research Part B: Methodological.* **43**(6), pp.625-642.

Peeta, S. and Ziliaskopoulos, A. 2001. Foundations of dynamic traffic assignment: The past, the present and the future. *Networks and Spatial Economics.* **1**(3-4), pp.233-265.

Pilvar, R. 2004. *A comparison of two dynamic travel time methodologies*. MSc(Eng) thesis, University of Leeds.

Pilvar, R. 2009. *A46 Groby Resurfacing Scheme - Journey Time Reliability Report.* AONE+ Consortium.

Pilvar, R. 2012. Development of an optimisation framework for scheduling of street works. In: *25th European Conference on Operational Research*, *8-11 July 2012, Vilnius, Lithuania*.

Poli, R. et al. 2008. *A field guide to genetic programming.* [Online]. Lulu Enterprises Uk Ltd. [Accessed 18 March 2014]. Available from: http://dces.essex.ac.uk/staff/rpoli/gp-field-guide/A_Field_Guide_to_Genetic_Programming.pdf

PTV Group. 2014. *Traffic Simulation with PTV Vissim.* [Online]. [Accessed 24 October 2014]. Available from: http://vision-traffic.ptvgroup.com/en-uk/products/ptv-vissim/

Radvanovsky, R. and McDougall, A. 2013. *Critical Infrastructure: Homeland Security and Emergency Preparedness* Borca Raton, US: CRC Press.

Redd, L. and Schneider, G. 1996. Systems dynamics approach to the transportation sector. *Transportation Quarterly.* **50**(1), pp.133-145.

Research and Innovative Technology Administration (RITA). 2014. *Vehicle-to-Vehicle (V2V) Communications for Safety.* [Online]. Available from: http://www.its.dot.gov/research/v2v.htm

Robinson, S. 2005. *The development and application of an urban link travel time model using data derived from inductive loop detectors*. Ph.D thesis, Imperial College London.

Rodríguez-Núñez, E. and García-Palomares, J.C. 2014. Measuring the vulnerability of public transport networks. *Journal of Transport Geography.* **35**, pp.50-63.

Rogers, M. and Duffy, A. 2012. *Engineering Project Appraisal.* 2nd ed. Chichester Willey-Blackwell.

Rose, G. et al. 1989. Estimating travel time functions for urban roads: options and issues. *Transportation Planning and Technology.* **14**(1), pp.63-82.

Rosen, S. 1974. Hedonic prices and implicit markets: product differentiation in pure competition. *The journal of political economy.* **82**(1), pp.34-55.

Ross, T. 2013. *Fuzzy logic with engineering applications.* [Online]. 3rd ed. Chichester: Wiley. [Accessed 18 February 2015]. Available from: http://ruangbacafmipa.staff.ub.ac.id/files/2012/02/ebooksclub.org__Fuzzy_Logic_with_Engineering_Applications__Third_Edition.pdf

Rothwell, B. 2014. *Bracknell Forest Chooses Yotta Mayrise Street Works Software.* [Online]. [Accessed 27 July 2014]. Available from: http://www.directionsmag.com/pressreleases/bracknell-forest-chooses-yotta-mayrise-street-works-software/390437

Rudjito, D. 2006. *The Application of Fuzzy Logic to Traffic Assignment in Developing Countries*. Ph.D thesis, Imperial College London.

Runarsson, T.P. and Yao, X. 2000. Stochastic ranking for constrained evolutionary optimization. *IEEE Transactions on Evolutionary Computation.* **4**(3), pp.284-294.

Ryu, S. et al. 2014. A modified gradient projection algorithm for solving the elastic demand traffic assignment problem. *Computers & Operations Research.* **47**, pp.61-71.

Saaty, T.L. 1980. *The analytic hierarchy process: planning, priority setting, resource allocation.* New York: McGrawHill.

Samanta, S. and Jha, M.K. 2012. Applicability of Genetic and Ant Algorithms in Highway Alignment and Rail Transit Station Location Optimization. *International Journal of Operations Research and Information Systems.* **3**(1), pp.13-36.

Shachter, R. 1988. Probabilistic inference and influence diagrams. *Operations Research.* **36**(4), pp.589-604.

Sheffi, Y. 1985. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods.* Englewood Cliffs, New Jersey: Prentice-Hall.

Shen, W. and Zhang, H.M. 2014. System optimal dynamic traffic assignment: Properties and solution procedures in the case of a many-to-one network. *Transportation Research Part B: Methodological.* **65**, pp.1-17.

Shepherd, S. and Sumalee, A. 2004. A Genetic Algorithm Based Approach to Optimal Toll Level and Location Problems. *Networks and Spatial Economics.* **4**(2), pp.161-179.

Shi, F. et al. 2014. Optimization method of alternate traffic restriction scheme based on elastic demand and mode choice behavior. *Transportation Research Part C: Emerging Technologies.* **39**, pp.36-52.

Sinha, A. 2015. *Evolutionary Bilevel Optimization.* [Online]. [Accessed 20 February 2015]. Available from: http://bilevel.org/applications/

Sipahi, S. and Timor, M. 2010. The analytic hierarchy process and analytic network process: an overview of applications. *Management Decision.* **48**(5), pp.775-808.

Song, Z. and Yin, Y. 2008. *Impact of Lane Closures on Roadway Capacity. Part C: Modeling Diversion Propensity at Work Zones.* [Online]. Transportation Research Centre at the University of Florida. [Accessed 20 February 2015]. Available from: http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_RD/FDOT_BD545_61_C.pdf

Srinivasan, K. 2002. Transportation Network Vulnerability Assessment: A Quantative Framework. *SECURITY PAPERS.* [Online]. Southeastern Transportation Center, pp.60-79. Available from: http://eng.odu.edu/transportation/khattak/06_Research%20Reports/9%20STC_security.pdf#page=64

Sugeno, M. 1985. *Industrial applications of fuzzy control.* New York: Elsevier Science Inc.

Sumalee, A. et al. 2013. Dynamic stochastic journey time estimation and reliability analysis using stochastic cell transmission model: Algorithm and case studies. *Transportation Research Part C: Emerging Technologies.* **35**, pp.263-285.

Sumalee, A. and Watling, D. 2008. Partition-based algorithm for estimating transportation network reliability with dependent link failures. *Journal of Advanced Transportation.* **42**(3), pp.213-238.

Sumalee, A. et al. 2006. Reliable network design problem: case with uncertain demand and total travel time reliability. *Transportation Research Record: Journal of the Transportation Research Board.* **1964**(1), pp.81-90.

Sun, H. et al. 2014. Reliability-based traffic network design with advanced traveler information systems. *Information Sciences.* **287**, pp.121-130.

Suwansirikul, C. et al. 1987. Equilibrium decomposed optimization: a heuristic for the continuous equilibrium network design problem. *Transportation Science.* **21**(4), pp.254-263.

Tang, Y. et al. 2010. *Optimization of Work Zone Schedule Considering Time-varying Traffic Diversion.* [Online]. Washington D.C.: Transportation Research Board (TRB). [Accessed 20 February 2015]. Available from: https://www.workzonesafety.org//files/documents/database_documents/TRB2010paper_Tang.pdf

Taylor, M.A. and D'Este, G.M. 2007. Transport network vulnerability: a method for diagnosis of critical locations in transport infrastructure systems. In: Murray, A.T. and Grubesic, T.H. eds. *Critical Infrastructure Advances in Spatial Science.* USA: Springer Berlin Heidelberg, pp.9-30.

Teodorovic, D. 1998. Fuzzy logic systems for transportation engineering: the state of the art. *Transportation Research Part A.* **33**(5), pp.337-364.

Teodorovic, D. and Kalic, M. 1996. Solving the modal split problem by fuzzy rules generated by learning from examples (in Serbian). *Proceedings Information Technologies.* pp.48-54.

Teodorovic, D. and Kikuchi, S. 1990. Transportation route choice model using fuzzy inference technique. In: *First International Symposium on Uncertainty Modeling and Analysis*, *3-5 December 1990, College Park, MD, USA*. Maryland: IEEE, pp.140-145.

The Geographic Information Panel. 2008. *Place matters: the Location Strategy for the United Kingdom.* [Online]. London: Communities and Local Government. [Accessed 10 February 2015]. Available from: http://data.gov.uk/sites/default/files/uk-location-strategy_10.pdf

The Institution of Civil Engineers (ICE). 2009. *THE STATE OF THE NATION DEFENDING CRITICAL INFRASTRUCTURE.* [Online]. Available from:

https://www.ice.org.uk/getattachment/5e93aedd-3b4c-44db-acfa-d176e0ccbb0e/State-of-the-Nation--Defending-Critical-Infrastruc.aspx

The Institution of Civil Engineers (ICE). 2014. *VISTA (Visualising integrated information on buried assets to reduce streetworks).* [Online]. [Accessed 6 October 2014]. Available from: http://www.ice.org.uk/Information-resources/Document-Library/VISTA-Visualising-integrated-information

The Surevey Association. 2011. *The Essential Guide to Utility Surveys.* [Online]. 4th ed. TSA. Available from: http://www.tsa-uk.org.uk/updated-essential-guide-to-utility-surveys/

Torlak, G. et al. 2011. Analyzing business competition by using fuzzy TOPSIS method: An example of Turkish domestic airline industry. *Expert Systems with Applications.* **38**(4), pp.3396-3406.

Transport for London (TfL). 2014. *London's register of roadworks.* [Online]. [Accessed 31 July 2014]. Available from: http://public.londonworks.gov.uk/roadworks/home;jsessionid=0aeae16430d6dd03effa30fb4d648bb3ec6c95065efb.e34NaxyLchaMci0QaxiQahmRbxr0

Transportation Research Board (TRB). 2003. *Transportation Planning and Management for Special Events: A Synthesis of Highway Practice.* [Online]. WASHINGTON D.C.: TRB. [Accessed)12 February 2015]. Available from: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_309a.pdf

Transportation Research Board (TRB). 2014. *Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools Application Guidelines.* [Online]. [Accessed 9 February 2015]. Available from: http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2prepubL04ApplicationGuidelines.pdf

Transportation Research Board (TRB). 2010. *Highways Capacity Manual.* Washington D.C.: TRB Publications.

TRL. 2007. *DRUM (Dynamic Roadspace Utilisation Manager).* [Online]. [Accessed 23 July 2014]. Available from: http://trl.co.uk/case-studies/traffic-management-drum/

TRL. 2014. *CONTRAM 5: An enhanced traffic assignment model.* [Online]. [Accessed 8 May 2014]. Available from: http://www.trl.co.uk/online_store/reports_publications/trl_reports/cat_traffic_engineering/report_contram_5_an_enhanced_traffic_assignment_model.htm

Tzeng, G. and Tsaur, S. 1997. Application of multiple criteria decision making for network improvement. *Journal of Advanced Transportation.* **31**(1), pp.49-74.

Ukkusuri, S. and Waller, S. 2006. Single-point approximations for traffic equilibrium problem under uncertain demand. *Journal of the Transportation Research Board.* **1964**(1), pp.169-175.

University of Florida. 2014. *CORSIM Microscopic Traffic Simulation Model.* [Online]. [Accessed 24 October 2014]. Available from: http://www-mctrans.ce.ufl.edu/featured/TSIS/version5/corsim.htm

University of Leeds. 2009. *Visualising Integrated information on buried assets to reduce streetworks (VISTA).* [Online]. [Accessed 17 February 2015]. Available from: http://www.comp.leeds.ac.uk/mtu/vista.htm

Unnikrishnan, A. and Lin, D. 2012. User Equilibrium with Recourse: Continuous Network Design Problem. *Computer-Aided Civil and Infrastructure Engineering.* **27**(7), pp.512-524.

Unnikrishnan, A. and Waller, S. 2009. User equilibrium with recourse. *Networks and Spatial Economics.* **9**(4), pp.575-593.

Van Vliet, D. et al. 2015. *SATURN Version 11.3 Manual.* [Online]. [Accessed 22 February 2015]. Available from: https://saturnsoftware.co.uk/saturnmanual/pdfs/SATURN%20v11.3.10%20Manual%20(All).pdf

Varia, H.R. et al. 2013. Application of genetic algorithms for joint optimization of signal setting parameters and dynamic traffic assignment for the real network data. *Research in Transportation Economics.* **38**(1), pp.35-44.

Waller, S. and Ziliaskopoulos, A. 2001. Stochastic Dynamic Network Design Problem. *Transportation Research Record: Journal of the Transportation Research Board.* **1771**(1), pp.106-113.

Wang, D. and Lo, H. 2010. Global optimum of the linearized network design problem with equilibrium flows. *Transportation Research Part B: Methodological.* **44**(4), pp.482-492.

Wang, J.Y.T. et al. 2013. A bi-objective user equilibrium model of travel time reliability in a road network. *Transportation Research Part B: Methodological.* **66**, pp.4-15.

Wang, L.X. and Mendel, J.M. 1992. Generating fuzzy rules by learning from examples. *IEEE Transactions on Systems, Man and Cybernetics.* **22**(6), pp.1414-1427.

Wang, W. and Feng, X. 2013. Research on integrated optimization of logistics network based on economic induction effect. *Journal of Wuhan University of Technology (Transportation Science and Engineering).* **2013**(6), pp.1143-1147.

Watling, D. 2008. *Modelling and Evaluation of Reliability Impacts in Road Networks: Concepts and Methods for Traffic Assignment Models.* [Online]. [Accessed 22 February 2015]. Available from: http://abstracts.aetransport.org/paper/index/id/3050/confid/14

Watling, D. 2009. *TRAN5290 NETWORK ANALYSIS MODELS Lecture Notes on Modelling Highway Networks*. January - May 2009, Institute for Transport Studies (ITS) at Leeds University.

Watling, D. 2009. *TRAN5290 NETWORK ANALYSIS MODELS Lecture Notes on Network Reliability*. January - May 2009, Institute for Transport Studies (ITS) at Leeds University. University of Leeds.

Watling, D. 2009. *TRAN5290 NETWORK ANALYSIS MODELS Lecture Notes on User Equilibrium with Elastic Demand* January - May 2009, Institute for Transport Studies (ITS) at Leeds University. University of Leeds.

Watling, D. and Balijepalli, N.C. 2012. A method to assess demand growth vulnerability of travel times on road network links. *Transportation Research Part A: Policy and Practice.* **46**(5), pp.772-789.

Watling, D. et al. 2012. Network impacts of a road capacity reduction: Empirical analysis and model predictions. *Transportation Research Part A: Policy and Practice.* **46**(1), pp.167-189.

Watling, D.P. and Cantarella, G.E. 2013. Modelling sources of variation in transportation systems: theoretical foundations of day-to-day dynamic models. *Transportmetrica B: Transport Dynamics.* **1**(1), pp.3-32.

Weber, A. 1929. *Alfred Weber's theory of the location of industries.* Chicago: The University of Chicago Press.

Wen, M. and Iwamura, K. 2008. Fuzzy facility location-allocation problem under the Hurwicz criterion. *European Journal of Operational Research.* **184**(2), pp.627-635.

Weng, J. and Meng, Q. 2013. Estimating capacity and traffic delay in work zones: An overview. *Transportation Research Part C: Emerging Technologies.* **35**, pp.34-45.

Wismans, L.J.J. et al. 2011. Comparison of Evolutionary Multi Objective Algorithms for the Dynamic Network Design Problem. In: *International Conference on Networking, Sensing and Control*, *11-13 April 2011, Delft, Netherlands*. IEEE, pp.275-280.

Wismans, L.J.J. et al. 2014. Accelerating solving the dynamic multi-objective network design problem using response surface methods. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations.* **18**(1), pp.17-29.

Wuliang, P. and Chengen, W. 2009. A multi-mode resource-constrained discrete time-cost tradeoff problem and its genetic algorithm based solution. *International journal of project management.* **27**(6), pp.600-609.

Xie, J. et al. 2013. Quadratic approximation and convergence of some bush-based algorithms for the traffic assignment problem. *Transportation Research Part B: Methodological.* **56**, pp.15-30.

Xu, L. 2006. *Urban Road Transportation Network Design Problem Based on Reliability Analysis*. Ph.D thesis, Beijing Jiaotong University.

Xu, W. and Chan, Y. 1993. Estimating an originâ€• destination matrix with fuzzy weights. *Transportation Planning and Technology.* **17**, pp.145-163.

Yang, H. and Bell, M.G.H. 1998. A capacity paradox in network design and how to avoid it. *Transportation Research Part A: Policy and Practice.* **32**(7), pp.539-545.

Yang, H. and Bell, M.G.H. 2001. Transport bilevel programming problems: recent methodological advances. *Transportation Research B: Methodological.* **35**(1), pp.1-4.

Yang, H. and Wang, J. 2002. Travel time minimization versus reserve capacity maximization in the network design problem. *Transportation Research Record: ournal of the Transportation Research Board.* **1783**(1), pp.17-26.

Yang, N. 2010. *Optimization of highway work zone decisions considering Short-term and Long-term Impacts*. Ph.D thesis, University of Maryland.

Yang, Y. et al. 2013. Optimization of variable speed limits for efficient, safe, and sustainable mobility. *Transportation Research Record - Network*

Modelling 2013. [Online]. **1**, pp.37-45. [Accessed 9 February 2015]. Available from: http://trid.trb.org/view.aspx?id=1241201

YIN, H. and XU, L. 2010. Vulnerability Assessment of Transportation Road Networks. *ournal of Transportation Systems Engineering and Information Technology.* **3**, pp.8-14.

Yin, Y. 2000. Genetic-algorithms-based approach for bilevel programming models. *Journal of Transportation Engineering.* **126**(2), pp.115-120.

Yin, Y. 2002. Multiobjective bilevel optimization for transportation planning and management problems. *Journal of Advanced Transportation.* **36**(1), pp.93-105.

Yu, B. et al. 2005. Optimizing bus transit network with parallel ant colony algorithm. In: *Proceedings of the Eastern Asia Society for Transportation Studies*, pp.374-389.

Zadeh, L. 1965. Fuzzy Sets. *Information and Control.* **8**, pp.338-353.

Zeng, J. et al. 2007. Application of a fuzzy based decision making methodology to construction project risk assessment. *International Journal of Project Management.* **25**(6), pp.589-600.

Zeng, X. and Zhang, Y. 2013. Development of Recurrent Neural Network Considering Temporal-Spatial Input Dynamics for Freeway Travel Time Modeling. *Computer-Aided Civil and Infrastructure Engineering.* **28**(5), pp.359-371.

Zhang, G. and Chen, J. 2010. Solving multi-class traffic assignment problem with genetic algorithm. In: *2010 Second International Conference on Computational Intelligence and Natural Computing, Wuhan*. IEEE, pp.229-232.

Zhang, N. et al. 2013. Road Network Capacity Reliability based on Transfer Hubs. *Procedia - Social and Behavioral Sciences.* **96**, pp.1976-1986.

Zheng, H. et al. 2014. Measuring Networkwide Traffic Delay in Schedule Optimization for Work-Zone Planning in Urban Networks. *IEEE Transactions on Intelligent Transportation Systems.* **15**(6), pp.2595 - 2604.

ZHENG, Y. et al. 2011. Carrying Capacity Reliability of Railway Networks. *Journal of Transportation Systems Engineering and Information Technology.* **11**, pp.16-21.

Zhou, X. et al. 2010. *DTALite: An Open-Source Fast Dynamic Traffic Assignment Engine.* [Online]. [Accessed 3 March 2014]. Available from: https://sites.google.com/site/dtalite/project-definition

Zhu, F. and Ukkusuri, S.V. 2014. A reinforcement learning approach for distance-based dynamic tolling in the stochastic network environment. *Journal of Advanced Transportation.*

Zietsman, D. and Vanderschuren, M. 2014. Analytic Hierarchy Process assessment for potential multi-airport systems - The case of Cape Town. *Journal of Air Transport Management.* **36**, pp.41-49.

Zlatanova, S. et al. 2012. *Intelligent Systems for Crisis Management.* [Online]. Springer. [Accessed 9 February 2015]. Available from: http://www.springer.com/earth+sciences+and+geography/geographical+information+systems/book/978-3-642-33217-3